PUGET SOUND AND APPROACHES

A Literature Survey

VOLUME III

Physical Oceanography
Marine Biology
General Summary

University of Washington Department of Oceanography
Seattle 5, Washington

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SEATTLE 5, WASHINGTON

PUGET SOUND AND APPROACHES
A LITERATURE SURVEY

Volume III

Work Performed Under

Contract No. Nonr-447(00)

Task Order 477(06)

of the

Office of Naval Research

June, 1954

Richard H. Fleming
Executive Officer

ACKNOWLEDGMENT

The material for this report has been arranged and coordinated by Mr. Peter M. McLellan under the technical supervision of Dr. Clifford A. Barnes.

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FOREWORD

The Literature Survey of Puget Sound and Approaches has been completed by the Department of Oceanography of the University of Washington as authorized by the Office of Naval Research Contract Nonr-447(00), Task Order 477(06). Under the terms of this contract the Department of Oceanography has provided a listing and analysis of all published and unpublished literature pertaining to the oceanography and factors influencing the oceanography of Puget Sound.

To effectively accomplish general oceanographic research in an area in which outside influences of every type play an important or undetermined role, every possible factor must be taken into consideration. For this reason all of the factors that may influence the oceanography of Puget Sound have been included. The form of the paper is essentially that of an abstract of the current knowledge on each subject. Appended to each subject is a detailed, annotated bibliography of all relevant publications and unpublished reports and data, whether used in the abstract or not. If no information is available on a certain subject this has been mentioned in order to present the status of our knowledge to date.

PUGET SOUND AND APPROACHES
A LITERATURE SURVEY

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30 June 1954

PHYSICAL OCEANOGRAPHY

TIDES

INTRODUCTION

The tide in the Puget Sound area is of the mixed type characterized by marked variation in the successive heights of low water. Significant changes occur in range and characteristics with both time and location. Port Townsend, near the entrance, has a mean tide range of 5 feet and a diurnal tide range of 8 feet. The southern extremities of Puget Sound, in the vicinity of Olympia, have mean and diurnal tide ranges of 11 and 15 feet, respectively. Periodically the tides at Port Townsend lose their mixed characteristics and become virtually diurnal for several days each month. However, this effect does not extend for any great distance into the Puget Sound system.

The tidal prism amounts to approximately 5 percent of the volume below the mean lower low water datum.

TIDE STATIONS

Table 10-1 and Figure 10-1 name and locate the tidal bench marks in Puget Sound where tide observations have been made. Shown also are four additional stations: Partridge Point, A; Oak Bay, B; Point No Point, C; Hyde Point, D; and Dufflemyer Point, E: for which nonharmonic tidal constants are published (U.S. Department of Commerce Coast and Geodetic Survey 1949-53).

Tide stations can be conveniently placed in three categories:

1. Reference stations;
2. Subordinate stations for which harmonic constants have been derived;
3. Subordinate stations for which harmonic constants have not been derived.

Puget Sound contains two reference stations and five additional stations for which tidal harmonic constants have been determined by the United States Coast and Geodetic Survey. A total of 55 stations have been established where tide observations have been made but for which harmonic constants are not available.

Reference Stations

Complete tidal predictions for the two reference stations, Port

TABLE 10-1. Location of Tidal Bench Marks

INDEX MAP NUMBER	NAME
50	Port Townsend (Fort Worden), Admiralty Inlet
51	Fort Flagler, Marrowstone Island, Admiralty Inlet
52	Port Ludlow, Admiralty Inlet
53	Port Gamble, Hood Canal
54	Seabeck, Hood Canal
55	Union, Hood Canal
56	Kingston, Appletree Cove, Puget Sound
57	Point Jefferson, Puget Sound
58	Port Madison, Bainbridge Island, Puget Sound
59	Eagle Harbor, Bainbridge Island, Puget Sound
60	Port Blakely, Bainbridge Island, Puget Sound
61	Pleasant Beach and Vicinity, Rich Passage
62	Brownsville, Port Orchard
63	Poulsbo, Liberty Bay
64	Bremerton, Sinclair Inlet
65	Tracyton, Dyes Inlet
66	South Colby, Yukon Harbor
67	Burton, Quartermaster Harbor, Vashon Island
68	Gig Harbor, Puget Sound
69	Arletta, Hale Passage
70	Wauna, Carr Inlet
71	Home, Von Geldem Cove
72	Longbranch, Filuce Bay
73	Vaughn, Case Inlet
74	Allyn, Case Inlet
75	Walkers Landing, Pickering Passage
76	Hartstene Island, Pickering Passage
77	Church Point, Hammersley Inlet
78	Shelton, Oakland Bay
79	Arcadia, Totten Inlet
80	New Kamilche, Totten Inlet
81	Eld Inlet (1 mile N.E. of Rocky Point)

TABLE 10-1. Location of Tidal Bench Marks (continued).

INDEX MAP NUMBER	NAME
82	Olympia, Budd Inlet
83	Henderson Inlet (Libby Ranch)
84	Depont, Nisqually Reach
85	Steilacoom, Puget Sound
86	Tacoma, Commencement Bay
87	Desmoines, Puget Sound
88	Duwamish River (8th Ave. S.), South Park
89	Seattle, Elliott Bay
92	Edmonds, Puget Sound
93	Mukilteo, Possession Sound
94	Everett, Possession Sound
95	Tulalip, Possession Sound
96	Stanwood, Stillaguamish River
97	Coupeville, Penn Cove, Whidbey Island
98	Polnell Point (1.9 miles E. of), Whidbey Island
99	Fort Whitman, Goat Island, Skagit Bay
100	North Fork (entrance), Skagit River
101	North Fork (highway bridge), Skagit River
102	La Conner, Swinomish Slough
103	Swinomish Slough (N. end), Padilla Bay
104	Ala Spit, Whidbey Island, Skagit Bay
105	Pass Island, Deception Pass
106	Dewey, Yokeko Point, Fidalgo Island
121	Lofall
122	Bangor
A	Partridge Point
B	Oak Bay
C	Point No Point
D	Hyde Point, McNeil Island
E	Dofflemyer Point, Budd Inlet

Table from Index Map, Tidal Bench Marks, Washington (U.S. Department of Commerce Coast and Geodetic Survey 1946).

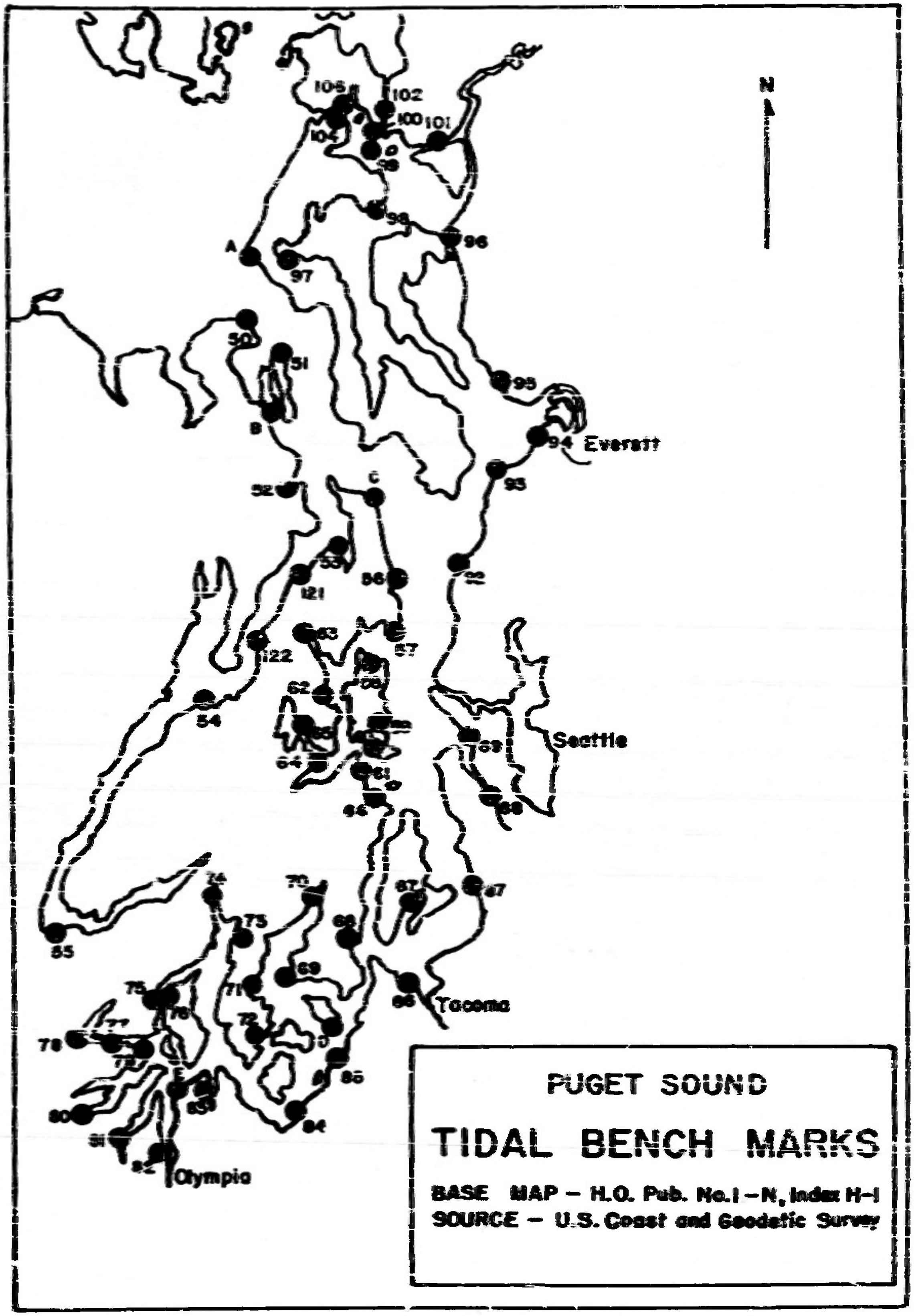

PUGET SOUND
TIDAL BENCH MARKS
BASE MAP – H.O. Pub. No. I – N, Index H-I
SOURCE – U.S. Coast and Geodetic Survey
N
Everett
Seattle
Tacoma
Olympia

Fig. 10-1

Townsend and Seattle, are obtained and published annually as times and heights of high and low waters for each day of the year (U.S. Department of Commerce Coast and Geodetic Survey 1949-53; Canada Department of Mines and Resources Annual). A complete set of tidal harmonic constants are published for these stations (U.S. Department of Commerce Coast and Geodetic Survey 1942).

SUBORDINATE STATIONS WITH HARMONIC CONSTANTS. Tidal harmonic constants for the two reference stations and Bremerton, Tacoma, Olympia, Everett, and Yokeko Point are given in Table 10-2 as H, the height in feet, and G, the Greenwich epoch in degrees of each constituent. See the list of Nomenclature following this section for a list and description of symbols used in this section.

SUBORDINATE STATIONS WITHOUT HARMONIC CONSTANTS. Published data for the remainder of the tide stations consists of values for the non-harmonic constants: high water interval, mean range of tide, and diurnal range of tide (U.S. Department of Commerce Coast and Geodetic Survey 1949-53); and the elevations referred to mean lower low water for the following planes: highest tide (estimated), mean higher high water, mean high water, half tide level, mean low water, mean lower low water, and lowest tide (estimated) (U.S. Department of Commerce Coast and Geodetic Survey n.d.). Table 10-3 gives this information for the Puget Sound tide stations.

Since the tides for all Puget Sound stations are similar to those for either Seattle or Port Townsend with different ranges and times of tide, a description of these two tides will suffice to illustrate the tides for the whole area.

SEATTLE TIDE

The tidal characteristics, determined from the harmonic constants of Table 10-2 and shown in Table 10-4, permit a description of the Seattle tide.

The tide is a pure mixed type with a large inequality in the low waters. The mean and diurnal ranges, 7.6 and 11.3 feet respectively, are appreciably larger than those for other Pacific Coast ports. For example: 4.2 and 5.8 feet for San Diego, 3.8 and 5.4 feet for Los Angeles, 3.9 and 5.7 feet for San Francisco, 6.5 and 8.2 feet for Astoria. The ratio of spring to neap ranges, approximately 1.6, is markedly less than that for the equilibrium tide while the ratio of perigean to apogean tides is approximately the same as for the equilibrium tide. This means

TABLE 10-2. Harmonic Constants for Puget Sound Tide Stations.

Constit-uent	PORT TOWNSEND		SEATTLE		BREMERTON		TACOMA		OLYMPIA		EVERETT		YOKEKO POINT	
	H*	G**	H	G	H	G	H	G	H	G	H	G	H	G
Sa	0.27	288	0.29	298	--	--	--	--	--	--	--	--	--	--
Ssa	0.13	225	0.09	224	--	--	--	--	--	--	--	--	--	--
K_1	2.46	271	2.72	277	2.69	282	2.73	277	2.88	287	2.69	277	2.81	279
O_1	1.44	250	1.50	256	1.47	259	1.51	255	1.56	264	1.49	255	1.54	255
P_1	0.76	268	0.84	275	0.80	280	0.84	273	0.84	286	0.76	275	(0.93)	(279)
Q_1	0.24	242	0.24	252	0.25	259	0.24	246	0.26	259	0.24	247	(0.30)	(243)
J_1	--	--	(0.15)	(289)	--	--	--	--	--	--	--	--	--	--
M_1	0.11	285	0.09	267	--	--	--	--	--	--	--	--	--	--
OO_1	--	--	(0.09)	(300)	--	--	--	--	--	--	--	--	--	--
$\mu\kappa_1=\rho_1$	--	--	(0.06)	(246)	--	--	--	--	--	--	--	--	--	--
$NJ_1=2Q_1$	--	--	(0.04)	(233)	--	--	--	--	--	--	--	--	--	--
S_1	--	--	0.05	19	--	--	--	--	--	--	--	--	--	--
M_2	2.14	250	3.51	11	3.60	18	3.75	12	4.77	30	3.39	11	3.25	18
S_2	0.51	13	0.86	38	0.83	43	0.90	40	1.13	64	0.81	38	0.91	45
N_2	0.45	321	0.69	341	0.72	348	0.73	341	0.90	3	0.68	340	0.70	342

*H = height in feet
**G = Greenwich epoch in degrees of each constituent

TABLE 10-2. Harmonic Constants for Puget Sound Tide Stations (Continued).

Constituent	PORT TOWNSEND		SEATTLE		BREMERTON		TACOMA		OLYMPIA		EVERETT		YOKEKO POINT	
	H*	G**	H	G	H	G	H	G	H	G	H	G	H	G
K_2	0.15	22	0.26	38	0.23	34	0.29	37	0.34	57	0.26	33	0.51	63
ν_2	0.09	329	0.15	358	--	--	--	--	--	--	--	--	(0.14)	(347)
$2MS_2=\mu_2$	0.08	237	0.11	242	--	--	--	--	--	--	--	--	(0.08)	(349)
L_2	0.10	36	0.19	73	--	--	--	--	--	--	--	--	(0.09)	(53)
T_2	0.08	36	0.16	24	--	--	--	--	--	--	--	--	--	--
$2N_2$	--	--	(0.09)	(311)	--	--	--	--	--	--	--	--	--	--
λ_2	0.03	51	(0.02)	(25)	--	--	--	--	--	--	--	--	--	--
R_2	--	--	(0.01)	(39)	--	--	--	--	--	--	--	--	--	--
M_3	--	--	0.04	158	--	--	--	--	--	--	--	--	--	--
M_4	0.13	61	0.07	199	--	--	--	--	--	--	--	--	0.05	232
MS_4	0.07	84	0.03	239	--	--	--	--	--	--	--	--	--	--
S_4	--	--	0.01	258	--	--	--	--	--	--	--	--	--	--
M_6	0.03	249	0.04	318	--	--	--	--	--	--	--	--	0.10	078
M_8	--	--	0.01	267	--	--	--	--	--	--	--	--	--	--

*H = height in feet
**G = Greenwich epoch in degrees of each constituent

Table summarized from various sources (U.S. Department of Commerce Coast and Geodetic Survey 1942, 1952b; Admiralty Hydrographic Department 1951; International Hydrographic Bureau 1933).

that the moon's parallax is just as effective as its phase in determining the range of the tides. The explanation of this fact is not clear, but is thought to be primarily associated with the bathymetry and thus the oscillatory characteristics of the Northeast Pacific. The ratio of tropic to mean diurnal inequality is only slightly less than that of the equilibrium tide, but the ratio of O_1/K_1 is significantly less than the corresponding ratio. The explanation of this phenomenon must also lie in the characteristics of the adjacent Pacific Basin. The mean interval between the moon's upper or lower transit and high water at Seattle is 4.36 hours (4 hours 22 minutes). This time lag becomes progressively greater for the stations farther north along the coast. The phase, parallax, and diurnal ages of the tide are 27, 55, and 19 hours, respectively. There seems to be no consistent variation of these quantities along the coast although the values of all the ages for the California ports are less than the above values for Seattle.

The Seattle Tide Curve for July 1928

The following discussion of the Seattle tide curve has been abstracted from Tides of Puget Sound and Adjacent Inland Waters (Bauer 1928).

The effects of the moon's changing declination, phase, and parallax, can be seen in the Seattle tide curve for July 1928 shown in Fig. 10-2. The beginning of the month finds the moon at its greatest distance south of the equator which is the time of tropic tides. It also happens to be full moon shortly after the moon has reached its greatest declination south, and judging by the time of perigee, the moon has scarcely passed its apogean distance in the first days of the month. The position of the sun (which changes less than 5 degrees in declination during the month) is not shown, since its small changes have relatively little effect on the tide.

The first striking features in the Seattle curve are the two high and two low waters in each day with a large inequality in the heights of the low waters. Increased average ranges (spring tides) occur near times of full and new moon while smaller average ranges (neap tides) occur at times of the moon's first and third quarters. It may be seen that the larger spring tides for this month are associated with the new moon. Likewise, the second neap period around the time of last quarter, shows somewhat smaller ranges than the first neap period. A similar variation of comparable magnitude can be seen to be associated with the perigean and apogean tides which lag the times of perigee and apogee, respectively, by about two days. This is evidenced by the fact that where perigee follows full moon, the maximum range also follows spring tide by several days but with comparable declination and where perigee precedes new moon, the maximum range occurs somewhat before the spring tides.

TABLE 10-3. Tidal Features of Puget Sound Stations

STATION	Station number	Latitude north °	Latitude north '	Longitude west °	Longitude west '	Mean high water lunitidal interval h m	Mean range of tide Feet	Diurnal range of tide Feet	Highest tide (estimated) Feet	Mean higher high water Feet	Mean high water Feet	Half tide level Feet	Mean lower water Feet	Mean lower low water Feet	Lowest tide (estimated) Feet	Diurnal tide range minus mean tide range Feet	$M_2 \pm 0.1$ Feet	$G(M_2)$ Degrees	$K_1 + O_1$ Feet	$K_1 + O_1/M_2$
Reference Station-Port Townsend																				
Partridge Point	A	48	14	122	46	3 43	4.5	7.7	--	7.7	--	--	--	0.00	--	3.2	7.9	353	3.9	2.1
Port Townsend	50	48	08	122	46	3 47	5.1	8.3	12.0	8.30	7.60	5.65	2.50	0.00	-4.5	3.2	2.2	355	3.9	1.8
Marrowstone Point	51	48	06	122	41	3 56	5.6	8.8	12.0	8.80	8.10	5.30	2.50	0.00	-4.5	3.2	2.4	359	3.9	1.6
Oak Bay	B	48	01	122	43	4 02	6.0	9.4	--	9.4	--	--	--	0.00	--	3.4	2.6	2	4.1	1.6
Reference Station-Seattle																				
Port Ludlow	52	47	55	122	41	4 08	6.3	9.9	13.5	9.90	9.10	5.95	2.80	0.00	-4.5	3.6	2.9	5	4.1	1.4
Port Gamble	53	47	51	122	35	4 11	6.7	10.3	14.0	10.30	9.50	6.15	2.80	0.00	-4.5	3.7	3.0	6	4.2	1.4
Lofall	121	47	49	122	39	--	7.0	10.5	14.0	10.50	9.70	6.20	2.70	0.00	-4.5	3.5	3.2	--	4.0	1.3
Bangor	122	47	45	122	44	--	7.3	10.9	15.0	10.90	10.10	6.45	2.80	0.00	-4.5	3.6	3.3	--	4.1	1.2
Seabeck	54	47	38	122	50	4 23	7.8	11.6	15.0	11.60	10.70	6.80	2.90	0.00	-4.5	3.8	3.5	13	4.3	1.2
Union	55	47	21	123	06	4 27	8.0	11.8	15.0	11.80	10.90	6.90	2.90	0.00	-4.5	3.8	3.6	15	4.3	1.2
Point No Point	C	47	55	122	32	4 12	6.7	10.4	--	10.4	--	--	--	0.00	--	3.7	3.0	7	4.2	1.4
Edmonds	92	47	49	122	23	--	7.5	11.2	14.5	11.20	10.30	6.55	2.80	0.00	-4.5	3.7	3.4	--	4.2	1.2
Kingston	56	47	[illegible]	122	30	--	7.5	11.1	14.5	11.10	10.30	6.55	2.80	0.00	-4.5	3.6	3.4	--	4.1	1.2
Point Jefferson	57	47	45	122	28	--	7.3	10.9	14.5	10.90	10.10	6.45	2.80	0.00	-4.5	3.6	3.3	--	4.1	1.2

TABLE 10-3. Tidal Features of Puget Sound Stations (continued).

STATION	Station number	Latitude north °	Latitude north '	Longitude west °	Longitude west '	Mean high water lunitidal interval h	Mean high water lunitidal interval m	Mean range of tide Feet	Diurnal range of tide Feet	Highest tide (estimated) Feet	Mean higher high water Feet	Mean high water Feet	Half tide level Feet	Mean lower water Feet	Mean lower low water Feet	Lowest tide (estimated) Feet	Diurnal tide range minus mean tide range Feet	$M_2 \pm 0.1$ Feet	$G(M_2)$ Degrees	$K_1 + O_1$ Feet	$K_1 + O_1/M_2$
Port Madison	58	47	42	122	32	4	20	7.7	11.4	15.0	11.40	10.50	6.65	2.80	0.00	-4.5	3.7	3.5	10	4.2	1.2
Poulsbo	63	47	44	122	39	4	29	8.1	11.9	15.5	11.90	11.00	6.95	2.90	0.00	-4.5	3.8	3.6	15	4.3	1.2
Brownsville	62	47	39	122	37	4	29	8.0	11.7	15.0	11.70	10.80	6.80	2.80	0.00	-4.5	3.7	3.6	15	4.2	1.2
Bremerton	54	47	33	122	38	4	34	8.0	11.7	14.7	11.70	10.80	6.80	2.80	0.00	-4.5	3.7	3.6	18	4.2	1.2
Tracyton	55	47	37	122	40	4	57	8.6	12.3	16.0	12.30	11.40	7.10	2.80	0.00	-4.5	3.7	3.9	29	4.2	1.1
Seattle	89	47	36	122	20	4	29	7.6	11.3	14.8	11.32	10.46	6.64	2.81	0.00	-4.5	3.7	3.5	14	4.2	1.2
Duwamish River	88	47	32	122	19	4	34	7.5	11.1	15.0	11.10	10.24	6.50	2.76	0.00	-4.5	3.6	3.5	17	4.1	1.2
Eagle Harbor	59	47	37	122	31	--		7.8	11.5	15.0	11.50	10.60	6.70	2.80	0.00	-4.5	3.7	3.5	--	4.2	1.2
Port Blakely	60	47	36	122	30	4	30	7.8	11.5	15.0	11.50	10.60	6.70	2.80	0.00	-4.5	3.7	3.5	15	4.2	1.2
Pleasant Beach	61	47	36	122	32	4	29	7.8	11.5	15.0	11.50	10.60	6.70	2.80	0.00	-4.5	3.7	3.5	15	4.2	1.2
South Colby	66	47	31	122	32	4	29	7.9	11.6	15.0	11.60	10.70	6.75	2.80	0.00	-4.5	3.7	3.6	15	4.2	1.1
Desmoines	87	47	24	122	20	4	32	8.0	11.7	15.0	11.70	10.80	6.80	2.80	0.00	-4.5	3.7	3.6	16	4.2	1.1
Burton	67	47	23	122	28	4	35	8.2	11.9	15.5	11.90	11.00	6.90	2.80	0.00	-4.5	3.7	3.7	18	4.2	1.1
Gig Harbor	68	47	20	122	35	4	35	8.2	11.9	15.5	11.90	11.00	6.90	2.80	0.00	-4.5	3.7	3.7	18	4.2	1.1
Tacoma	86	47	17	122	25	4	35	8.1	11.8	15.5	11.80	10.90	6.85	2.80	0.00	-4.5	3.7	3.7	18	4.2	1.1
Arletta	69	47	17	122	40	4	53	9.4	13.3	17.0	13.30	12.40	7.70	3.00	0.00	-4.5	3.9	4.3	27	4.4	1.0
Home	71	47	16	122	45	4	54	9.7	13.6	17.0	13.60	12.70	7.85	3.00	0.00	-4.5	3.9	4.4	27	4.4	1.0
Wauna	70	47	23	122	38	4	55	9.7	13.6	17.0	13.60	12.70	7.85	3.00	0.00	-4.5	3.9	4.4	28	4.4	1.0

TABLE 10-3. Tidal Features of Puget Sound Stations (continued).

STATION	Station number	Latitude north °	'	Longitude west °	'	Mean high water lunitidal interval h	m	Mean range of tide Feet	Diurnal range of tide Feet	Highest tide (estimated) Feet	Mean higher high water Feet	Mean high water Feet	Half tide level Feet	Mean lower water Feet	Mean lower low water Feet	Lowest tide (estimated) Feet	Diurnal tide range minus mean tide range Feet	$M_2 \pm 0.1$ Feet	$G(M_2)$ Degrees	$K_1 + O_1$ Feet	$K_1 + O_1/M_2$
Steilacoom	85	47	11	122	36	4	50	9.5	13.3	17.0	13.30	12.40	7.65	2.90	0.00	-4.5	3.8	4.3	25	4.3	1.0
Hyde Point	D	47	12	122	39	4	50	9.5	13.4	--	13.4	--	--	--	0.00	--	3.9	4.3	25	4.4	1.0
Sequalitchew Cr.	84	47	07	122	40	4	51	9.6	13.4	17.0	13.40	12.50	7.70	2.90	0.00	-4.5	3.8	4.4	25	4.3	1.0
Longbranch	72	47	13	122	45	4	52	9.8	13.7	17.0	13.70	12.80	7.90	3.00	0.00	-4.5	3.9	4.5	26	4.4	1.0
Henderson Inlet	83	47	09	122	50	4	53	10.0	14.0	17.5	14.0	13.00	8.00	3.00	0.00	-4.5	4.0	4.6	27	4.6	1.0
Vaughn	73	47	20	122	46	5	02	10.2	14.1	17.5	14.10	13.20	8.10	3.00	0.00	-4.5	3.9	4.6	31	4.4	1.0
Allyn	74	47	23	122	49	5	05	10.3	14.2	17.5	14.20	13.30	8.15	3.00	0.00	-4.5	3.9	4.7	33	4.4	0.9
Walkers Landing	75	47	17	122	56	5	01	10.3	14.3	18.0	14.30	13.30	8.15	3.00	0.00	-4.5	4.0	4.7	31	4.6	1.0
Hartstene Island	76	47	17	122	55	--		10.5	14.5	18.0	14.50	13.60	8.35	3.10	0.00	-4.5	4.0	4.8	--	4.6	1.0
Arcadia	79	47	11	122	56	4	59	10.6	14.5	18.0	14.50	13.60	8.30	3.00	0.00	-4.5	3.9	4.8	30	4.4	0.9
Church Point	77	47	12	123	01	--		11.1	14.9	18.5	14.90	13.90	8.35	2.80	0.00	-4.5	3.8	5.0	--	4.3	0.9
Shelton	78	47	13	123	05	5	56	10.8	14.3	18.0	14.30	13.40	8.00	2.60	0.00	-4.5	3.5	4.9	58	4.0	0.8
Burns Point	80	47	07	123	03	5	02	11.0	15.0	18.5	15.00	14.00	8.50	3.00	0.00	-4.5	4.0	5.0	32	4.6	0.9
Rocky Point	81	47	04	123	01	5	00	10.6	14.7	18.0	14.70	13.70	8.40	3.10	0.00	-4.5	4.1	4.8	31	4.7	1.0
Dofflemyer Point	E	47	08	122	54	4	55	10.5	14.4	--	14.4	--	--	--	0.00	--	3.9	4.8	28	4.4	0.9
Olympia	82	47	03	122	54	5	04	10.5	14.4	17.8	14.40	13.50	8.25	3.00	0.00	-4.7	3.9	4.8	32	4.4	0.9
Mukilteo	93	47	57	122	18	4	37	7.4	11.0	14.5	11.00	10.10	6.40	2.70	0.00	-4.5	3.6	3.4	18	4.1	1.2
Everett	94	47	59	122	13	4	28	7.4	11.1	14.5	11.10	10.20	6.50	2.80	0.00	-4.5	3.7	3.4	14	4.2	1.2

TABLE 10-3. Tidal Features of Puget Sound Stations (continued).

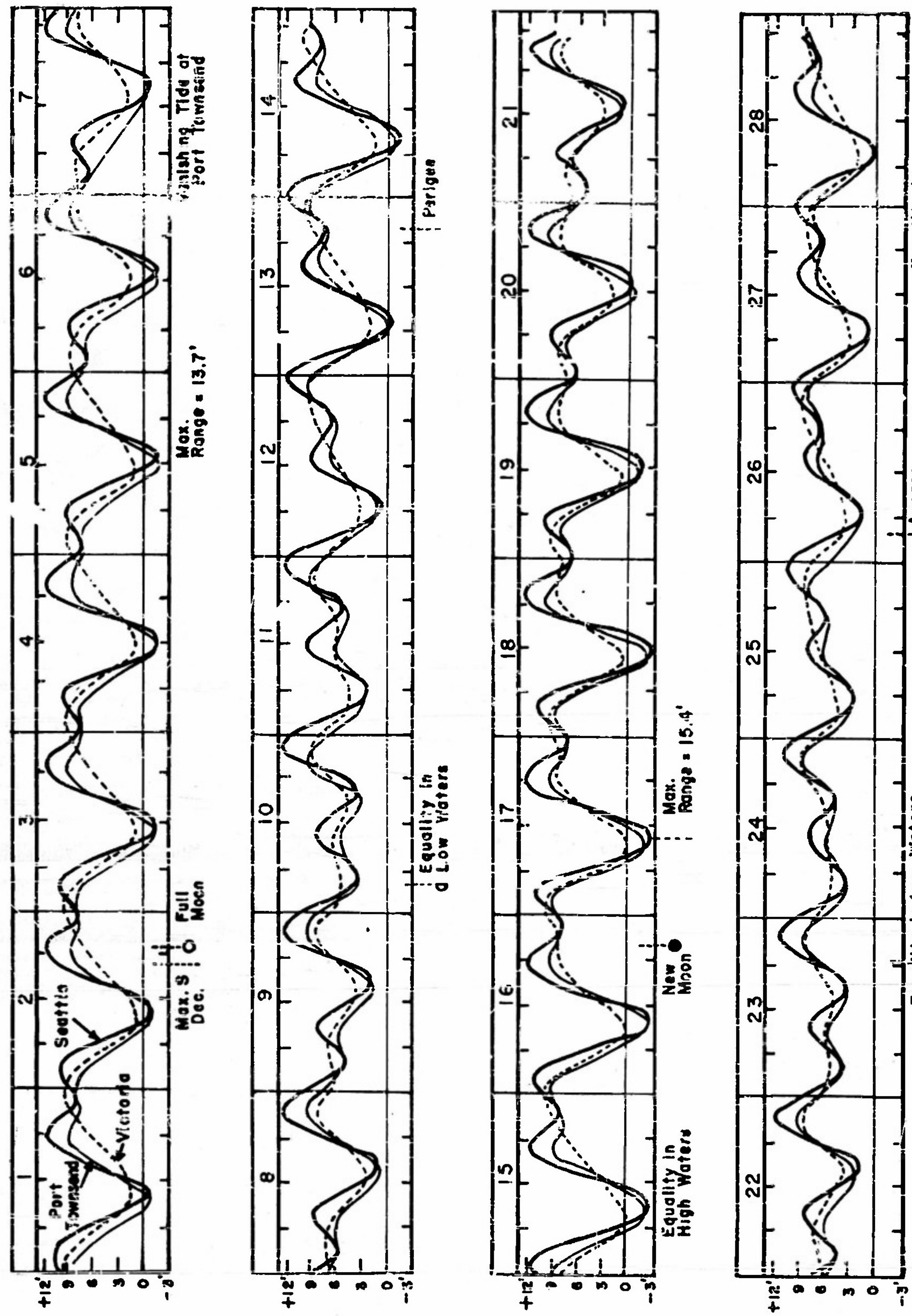
STATION	Station number	Latitude north °	'	Longitude west °	'	Mean high water lunitidal interval h	m	Mean range of tide Feet	Diurnal range of tide Feet	Highest tide (estimated) Feet	Mean higher high water Feet	Mean high water Feet	Half tide level Feet	Mean lower water Feet	Mean lower low water Feet	Lowest tide (estimated) Feet	Diurnal tide range minus mean tide range Feet	$M_2 \pm 0.1$ Feet	$G(M_2)$ Degrees	$K_1 + O_1$ Feet	$K_1 + O_1/M_2$
Tulalip	95	48	04	122	17	4	31	7.6	11.2	14.5	11.20	10.40	6.60	2.80	0.00	-4.5	3.6	3.5	15	4.1	1.2
Stanwood	96	48	14	122	22	4	46	5.7	7.4	10.5	7.40	6.50	3.65	0.80	0.00	--	3.7	2.6	23	4.2	1.6
Coupeville	97	48	13	122	41	4	39	7.8	11.5	14.5	11.50	10.60	6.70	2.80	0.00	-4.5	3.7	3.5	20	4.2	1.2
Polnell Point	98	48	17	122	31	--		7.7	11.5	14.5	11.50	10.60	6.75	2.90	0.00	-4.5	3.8	3.5	--	4.3	1.2
Fort Whitman	99	48	22	122	32	--		7.7	11.5	14.5	11.50	10.50	6.65	2.80	0.00	-4.5	3.8	3.5	--	4.3	1.2
North Fork, Skagit	100	48	22	122	31	--		5.8	7.6	--	7.60	6.70	3.80	0.90	0.00	--	1.8	2.6	--	2.1	0.8
North Fork, Skagit	101	48	22	122	25	--		4.0	5.0	--	5.00	4.20	2.20	0.20	0.00	--	1.0	1.8	--	1.1	0.6
La Conner	102	48	23	122	30	5	09	4.7	6.5	9.5	6.50	5.60	3.25	0.90	0.00	--	1.8	2.1	34	2.1	1.0
Ala Spit	104	48	24	122	35	--		6.9	10.5	13.5	10.50	9.60	6.15	2.70	0.00	-4.5	3.6	3.1	--	4.1	1.3
Pass Island	105	48	24	122	38	--		5.1	9.0	12.0	9.00	7.90	5.35	2.80	0.00	-4.5	3.9	2.3	--	4.4	1.9
Yokeko Point	106	48	25	122	37	4	54	7.3	11.2	14.0	11.20	10.10	6.45	2.80	0.00	-4.5	3.9	3.3	27	4.4	1.3

Table styled after Tide Tables (U.S. Department of Commerce Coast and Geodetic Survey 1949-53) with published data from several sources (U.S. Department of Commerce Coast and Geodetic Survey n.d., 1942, 1952b).

TABLE 10-4. Characteristics of Seattle and Port Townsend Tides.*

TIDAL CHARACTERISTICS		SEATTLE	PORT TOWNSEND
1. Type	(a) $\frac{K_1+O_1}{M_2+S_2}$	0.96	1.47
	(b) $M_2^o-K_1^o-O_1^o$	199°	189°
2. Range	(a) Mean range	7.6 ft.	5.1 ft.
	(b) Diurnal range	11.3 ft.	8.3 ft.
3. Spring range	(a) S_2/M_2	0.24	0.25
	(b) $\frac{1+S_2/M_2}{1-S_2/M_2}$	1.6	1.7
4. Perigean range	(a) N_2/M_2	0.20	0.21
	(b) $\frac{1+N_2/M_2}{1-N_2/M_2}$	1.5	1.5
5. Diurnal inequality	(a) O_1/K_1	0.55	0.59
	(b) $0.9(1+O_1/K_1)$	1.4	1.4
6. Lunitidal interval	$M_2^o/28.98$	4.36 hrs.	3.61 hrs.
7. Phase age	$\frac{S_2^o-M_2^o}{s_2-m_2}$	26.5 hrs.	22.6 hrs.
8. Parallax age	$\frac{M_2^o-N_2^o}{m_2-n_2}$	55 hrs.	53.3 hrs
9. Diurnal age	$\frac{K_1^o-O_1^o}{k_1-o_1}$	19 hrs.	19 hrs.

* For explanation of the various terms, refer to Appendix 10-A.



Monthly tidal curves for Seattle, Port Townsend, and Victoria, showing the effect of moon's phase, declination, apogee, and perigee.

Fig. 10-2

It remains to trace the influence of the moon's declination. As has been seen, it is merely a coincidence that the full moon and new moon occur at the same time as the tropic tide in this particular month. Likewise, it is due to this coincidence that the greatest inequality in low waters occurs at the time of spring tide. This inequality is really only associated with the degree of the moon's declination, either north or south. Two consecutive high waters show an inequality of only a foot or so at the beginning of the month, while the two consecutive low waters differ at that time by almost 9 feet. At the time of equatorial tide, the opposite takes place, as the low waters tend to become equal and the high waters reach a maximum of inequality. But, this maximum of inequality amounts only to 3 1/2 feet, so that the low water inequality becomes a dominant feature of the Seattle tide. In a similar way, for other months, the diurnal inequality will be modified by the slowly changing declination of the sun. When the sun is near the equator during March and September the smallest diurnal inequalities will occur while a maximum will be shown during June and December.

PORT TOWNSEND TIDE

The Port Townsend tide as seen in Table 10-3, is similar to Seattle's in most respects. The most evident difference is the value of the ratios of the diurnal to semidiurnal components $(K_1 + O_1)/(M_2 + S_2)$. While the value is in the range for a mixed type of tide, it lies close to that for a diurnal type of tide. Thus, the Port Townsend tide exhibits some diurnal characteristics, for one or two days in the month occur with a vanishing tide for which there is only one high water and one low water during the day. Other differences between the two tides are their range and time. The Port Townsend tide occurs on an average of 45 minutes earlier with a mean range two-thirds that of Seattle's.

The Port Townsend Tide Curve for July 1928

The following discussion of the Port Townsend tide curve has been abstracted from Tides of Puget Sound and Adjacent Inland Waters (Bauer 1928.

The Port Townsend tide curve for July 1928 is also shown in Fig. 10-2, where it can be compared with those for Seattle and Victoria. The tides here are affected by the moon's phase, declination, and parallax in the same manner that they are for Seattle, but the tide is more nearly diurnal with a decreased range and a somewhat earlier time of high water. Notice that there is only one high and one low water on the seventh of the month.

THE SEMIDIURNAL AND DIURNAL WAVES IN PUGET SOUND

In order to investigate the semidiurnal and diurnal waves in Puget Sound, it is necessary to determine values for the amplitudes and phases of the two waves from the nonharmonic constants for the stations given in Table 10-3. The amplitudes are given by the following relations, modified from Marmer:

M_2 = 0.43 x mean range, and

$K_1 + O_1$ = 1.22 x (diurnal range--mean range), where Port Townsend is the reference station;

M_2 = 0.455 x mean range, and

$K_1 + O_1$ = 1.14 x (dirunal range--mean range), where Seattle is the reference station.

(Marmer 1951).

The Greenwich epoch for the M_2 component, $G(M_2)$, is determined from the high water interval and longitude for each station. The phase of the diurnal wave cannot be determined from the available data, except for the stations having harmonic constants available. It appears that the change in phase between any two points of the diurnal wave is somewhat less than half that of the semidiurnal wave.

Figure 10-3 shows the amplitudes and Greenwich epochs of the principal semidiurnal (M_2) component for representative stations along the length of Puget Sound proper. Following Redfield (Redfield 1950) the horizontal axis is a distance scale consisting of the phase difference between the station in question and the head of the Sound at Shelton. For a simple rectangular gulf with no friction, the amplitude would vary as the cosine of the phase difference; the Greenwich epochs and the times of high water would be the same for all stations having a phase difference less than 1.57 radians. The semidiurnal amplitude distribution is relatively insensitive to Puget Sound's small frictional effects and can be primarily attributed to the effects of topography, except for Hammersley Inlet, where the amplitude is larger at Church Point than at Shelton or Arcadia, its two ends.

Since the lower end of the Sound consists of a number of separate arms, the effective length is not precisely determined, but the variation in amplitude from Arcadia to the north end of the Tacoma Narrows can be seen to follow a regular cosine shape. Here, an abrupt change occurs in slope, and the continuation of the curve has again a cosine shape but with decreased amplitude and apparently displaced towards the right. The explanation of this phenomenon is found in the sharp decrease in channel

cross section found in passing south through this point which causes a partial reflection of the incident tidal wave, thus decreasing the effective length of the southern Sound. The shifting of the curve to the right and decrease in amplitude then follows from the decrease in effective length. Between Seattle and Point No Point the opposite occurs: the slope is markedly increased since the effective length of that portion of the Sound south of this point is increased to where it joins with Possession Sound. This uniformly steep slope is maintained north through Admiralty Inlet to the entrance of Puget Sound.

The times of high water illustrate the effects of tidal friction, for if there were no friction high water would occur simultaneously at all places in Puget Sound. In Fig. 10-3 there can be seen three regions of greater, and two of lesser slope, in the curve for the times of high water. The regions of small slope correspond to those with large cross-sectional area and correspondingly weak currents. For practical purposes the time differences between these stations are unimportant. Large slopes are found where the channel is restricted in depth and width to such an extent that the average maximum tidal currents reach velocities of 2 knots or more. Here the frictional forces are large and the changes in times of high water are appreciable over relatively short distances.

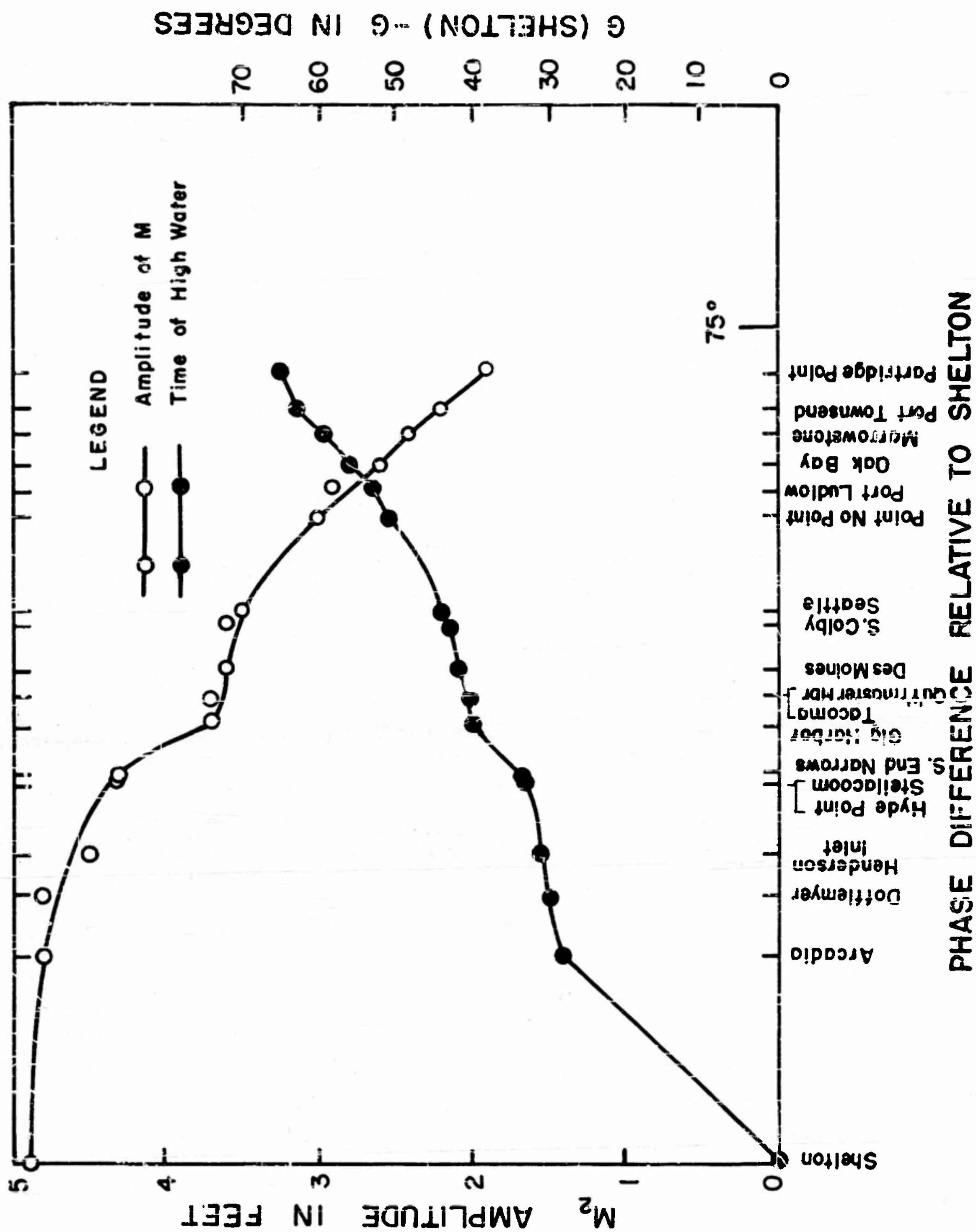
TIDAL DATUM PLANES

Tidal datum planes in common use are: sea level, half-tide level, and lower low water (Marmer 1951). Mean lower low water, the average height of the lower low waters over a 19-year period, is the datum for the charts of the Puget Sound region. Reference planes derived from averages over a period of a day, week, month, and year, are denoted by the terms daily, weekly, monthly, and yearly, respectively. It is to be expected that the values averaged over shorter periods of time undergo fortnightly, monthly, semiannual, annual, and 19-yearly variations in accordance with the variations in the tide-generating forces and the seasonal weather patterns. This is shown for Puget Sound in a study of the Seattle tidal datum planes (Marmer 1951).

Sea Level at Seattle

Relatively large daily variations in sea level associated with wind and weather, are well-known the world over. Abnormally high tides associated with the storms of 27 November, 30 November, and 5 December 1951, were found to be associated with changes in sea level up to about 2 feet. This is considered to be close to a maximum value for this region.

The annual variation in monthly sea level derived from 19 years of observations (1930-48), is shown in Marmer (Marmer 1951). A 0.52-foot difference between the highest sea level in December and lowest in August



The semidiurnal wave in Puget Sound.

Fig. 10-3

occurs which is more than ten times the range of the sun's annual and semiannual equilibrium tides. The annual variation in barometric pressure at Neah Bay (where the Strait of Juan de Fuca meets the Pacific Ocean) is able to account for about one-third of the 0.7-foot range in monthly sea level, leaving about two-thirds to be explained in some other manner. The difference in sea level between Neah Bay and Seattle is most likely accounted for by Puget Sound's prevailing southerly winter and northerly summer winds. The remaining portion of the annual variation is probably due to the changing wind and current pattern in the North Pacific Ocean.

The yearly sea level, as described by Marmer (Marmer 1951), undergoes much smaller changes than the monthly sea levels, generally changing less than 0.1 foot from year to year, although occasionally changing by as much as 0.2 or 0.3 foot. These changes in yearly sea level are similar for all the stations on the Pacific Coast of continental United States. A progressive rise is apparently taking place, which at Seattle amounted to somewhat less than 0.005 foot per year from 1898 to 1930, and 0.006 foot per year since 1930. These slow changes are apparently due to relative land movements, as sea level on the Alaskan coast has been falling during this time. For local changes in sea level see the section on Geology for additional discussion.

Half-Tide Level at Seattle

The difference between half-tide level (which lies exactly halfway between the planes of mean high water and mean low water) and sea level at any place depends upon the amplitude and phase relations between the various constituents of the tide at that place. For tides of the semidirunal and mixed types:

$$HTL-SL = M_4 \cos(2M_2^\circ - M_4^\circ) - 0.03(K_1 + O_1)^2 \cos(M_2^\circ - K_1^\circ - O_1^\circ)/M_2,$$

where HTL stands for half-tide level and SL for sea level. Figure 37 in Marmer (Marmer 1951) shows the annual variation of this difference for the 38-year period 1911 through 1948. The variation is nearly sinusoidal with a range of about 0.1 foot and a period of about 12 years.

Lower Low Water at Seattle

Daily variations in lower low water are partly of a periodic nature, due to the tide-generating forces, and partly nonperiodic, due to changes in sea level. The periodic change is evident from Fig. 10-2 which shows a range of 6 feet for the month.

In monthly low waters, these periodic variations are largely eliminated. Figures 50 and 52 in Marmer (Marmer 1951) show a maximum range of 1.5 feet with a semiannual period for the heights of monthly lower low water.

The semiannual variations will be averaged out in the value of annual lower low water leaving only the 19-year variation. Figures 53 and 54 in Marmer (Marmer 1951) show the range of this variation to be 0.6 foot.

TIDAL VOLUMES

The tidal volumes for the different areas of Puget Sound are given in the section on Hydrography.

PRESENT STUDIES

Tide gages are operated on Puget Sound by the following authorities: U.S. Coast and Geodetic Survey, U.S. Corps of Engineers, and the State Water Resources Commission.

The Coast and Geodetic Survey is carrying out the following tidal survey program (in addition to the primary station at Seattle):

Standard gage 1 year or more	Portable gage 2 months or more
Port Townsend	Port Ludlow
Cornet Bay	Union
Everett	Yukon Harbor
Tacoma	Gig Harbor
Olympia	Wauna
	Arletta
	Longbranch
	Allyn
	Arcadia
	Shelton
	Steilacoom
	Coupeville
	Polnell Point
	Ala Spit
	Possession Point
	Point Partridge

(U.S. Department of Commerce Coast and Geodetic Survey 1952c).

TIDAL CURRENTS

INTRODUCTION

The tidal currents in Puget Sound, while actuated by the same forces that bring about the tide, bear no constant relation to the height of the tide--either in time of occurrence--or velocity. The velocities normally increase with increasing tidal ranges. Also, the tidal currents are not subject to such large diurnal inequalities as the tides, although in some localities the lesser flood currents of the day are weak or absent altogether at times of maximum lunar declination. Normally, a net daily outflow occurs at the surface and a net daily inflow at depth. Exceptions occur where a net outflow or inflow may occur at all depths.

Currents are subject to wide local variations, being influenced by the subsurface topography of the channels and basins, river discharge, and meteorological conditions. Topographic effects are prominent in the Sound due to the irregular configuration of the channels. The greatest current velocities occur in the narrow and relatively shallow channels such as Admiralty Inlet, Tacoma Narrows, and Deception Pass, which have tropic velocities of 4.7, 5.1 and 7.2 knots, respectively. Velocities in the deeper, wider parts of the Sound, are generally much less than those occurring in the passes and narrows.

At the strength of the tidal currents, jet streams issue from the throats of constricted channels and apparently continue in force for considerable distances downstream. Laterally these jets may be flanked by slower currents or counter currents.

CURRENT STATIONS

There are three primary reference stations for Puget Sound tidal currents: Admiralty Inlet, Tacoma Narrows, and Deception Pass. The current tables furnish predictions for these stations for each day of the year for times of slack water and times and velocities of maximum flood and ebb currents (U.S. Department of Commerce Coast and Geodetic Survey 1952-53). In addition to the primary reference stations there are 83 subordinate stations listed in the current tables. Time differences and velocity ratios between the subordinate and reference stations are listed which make it possible for one to derive the maximum flood and ebb current velocities and the times of maximum ebb, flood, and slack waters at each subordinate station.

The current tables give the interval of time between current floods, the flood direction, the average current velocity at strength of current the tropic (maximum current due to astronomic causes) velocities for all

reference and subordinate stations. It should be emphasized that the currents shown in the current tables are based on observations made at a relatively shallow depth in order to be of use in predicting the effective current the average draft cargo vessel will encounter.

SURFACE TIDAL CURRENT DISTRIBUTION

Tidal current charts prepared by the U.S. Coast and Geodetic Survey (U.S. Department of Commerce Coast and Geodetic Survey 1948, 1952e) present a comprehensive view of the surface tidal current movement in the waterways of Puget Sound. These charts show the direction and speed of the current for numerous locations in the northern and southern parts of the Sound for each hour of the day. Time is reckoned from the times of maximum flood and maximum ebb current at Admiralty Inlet for the northern part of the Sound and at Tacoma Narrows for the southern part of the Sound. These charts are designed to be used with the current tables.

The British Columbia Pilot (Canada Department of Mines and Resources 1946) furnishes a description of the main features of the surface tidal currents of Puget Sound. The Pilot warns navigators of the following hazards:

> Tide rips whenever the wind opposes the surface current near:
>
> Apple Cove Point, Foulweather Bluff, Steilacoom, Point Wilson
>
> Strong currents near the following points and in the following bays, channels and passages:
>
> Admiralty Bay, Port Townsend Canal, Agate Passage, Rich Passage, Colvos Passage, Hale Passage, Squaxin Passage, Hammersley Inlet, Oro Bay, Skagit Bay, Deception Pass
>
> Strong eddies from the shore out toward the channel in Deception Pass and Port Townsend Canal.

The British Columbia Pilot also mentions that in many places in Puget Sound slack water occurs from half an hour to one hour earlier near the shore than in mid-channel.

Surface Tidal Currents in Admiralty Inlet

Figure 10-4 give the predicted current curve for Admiralty Inlet during the period 10 through 20 May 1947 showing its change with the moon's declination, phase, and parallax. At the beginning of the record (following the moon's maximum southerly declination on the 9th) there is a maximum of inequality in the flood currents, with only little inequality in the ebb currents. During the first five days with apogee on the 10th, and last quarter on the 13th, the mean currents remain somewhat low, giving no currents greater than 2 knots for the 12th and 13th. The inequality in the currents is minimum at the time of equatorial tides, even though the mean currents are increasing with the approach of new moon and perigee on the 20th and 22d, respectively. In the last days of the record the inequalities are also increasing with increasing north declination of the moon. A predominant ebb current is evident during this interval of time.

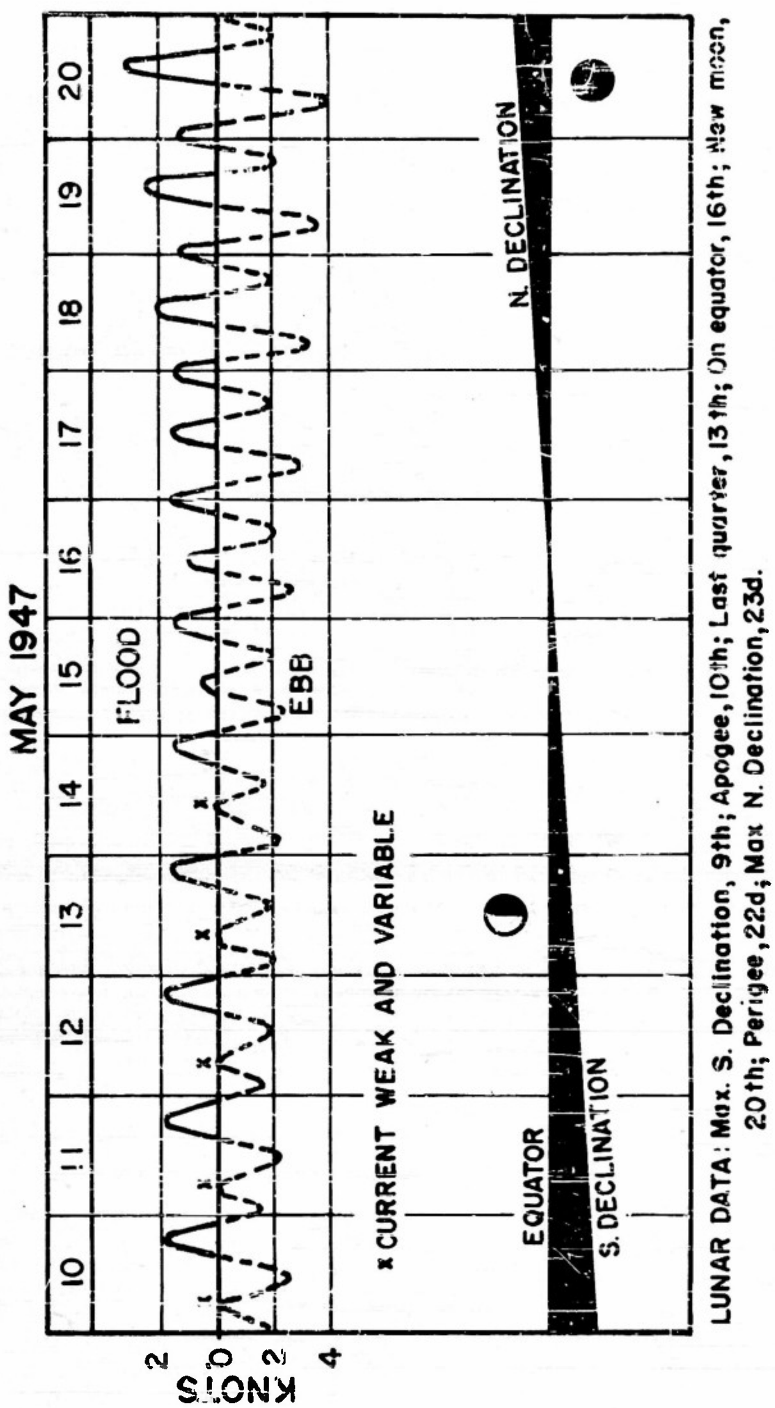
Figure 10-5 shows the relation between tide and current at Admiralty Inlet for 15 and 16 July 1928 (Bauer 1928). While it is evident that the stronger currents are associated with times of maximum change of tide, it is also clear that the relationship is not a constant one, since there is no fixed relation between current velocity and range of tide nor between time of slack water and maximum tide. Slack water may follow high or low water by anywhere up to three hours which is characteristic of mixed tides.

CURRENT FLUCTUATIONS

While the tidal currents in Puget Sound have two floods and two ebbs in each lunar day, they do not undergo a regular sinusoidal variation with time. As can be seen from Fig. 10-6, superimposed on the usual tidal changes there is a primary fluctuation of velocity with an average amplitude of the order of 0.1 knot and a period usually between 15 and 45 minutes. In the Tacoma Narrows and at stations not near mid-channel, the oscillations are much more extreme and the current motion becomes very complex.

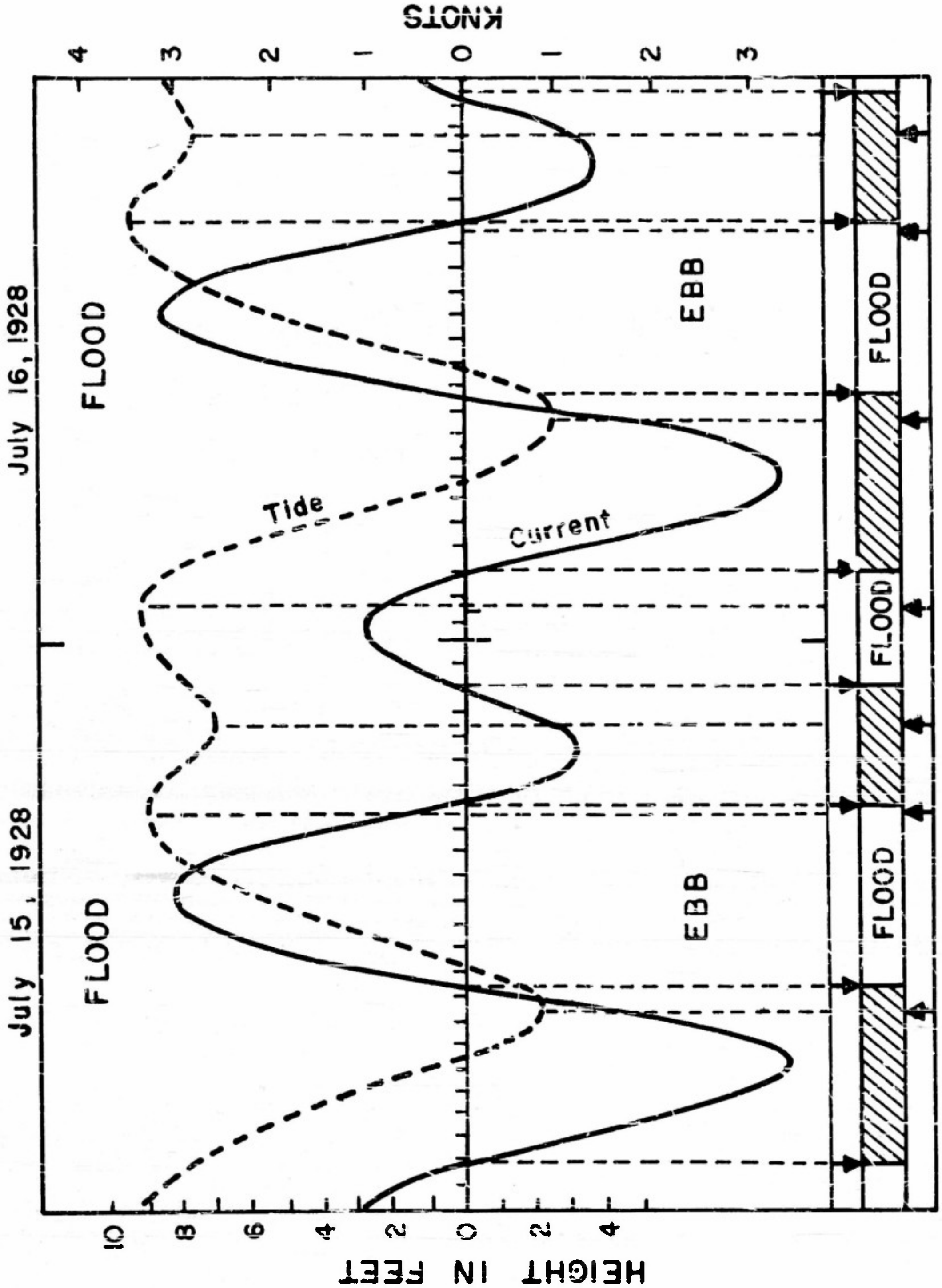
A secondary fluctuation averaging 0.05 knot in most places, but 0.2 knot in mid-channel in Tacoma Narrows, occurs with a period of about two minutes. There are apparently smaller fluctuations of even higher order in most cases.

These fluctuations in current are often associated with the passage of large scale eddies, the boundaries of which are frequently quite sharp and can be easily spotted from shipboard. Other possible causes include seiches and internal waves generated by the strong tidal currents in these channels with their rugged relief. The local wind is not a possible cause in this instance since these data were taken under calm conditions.



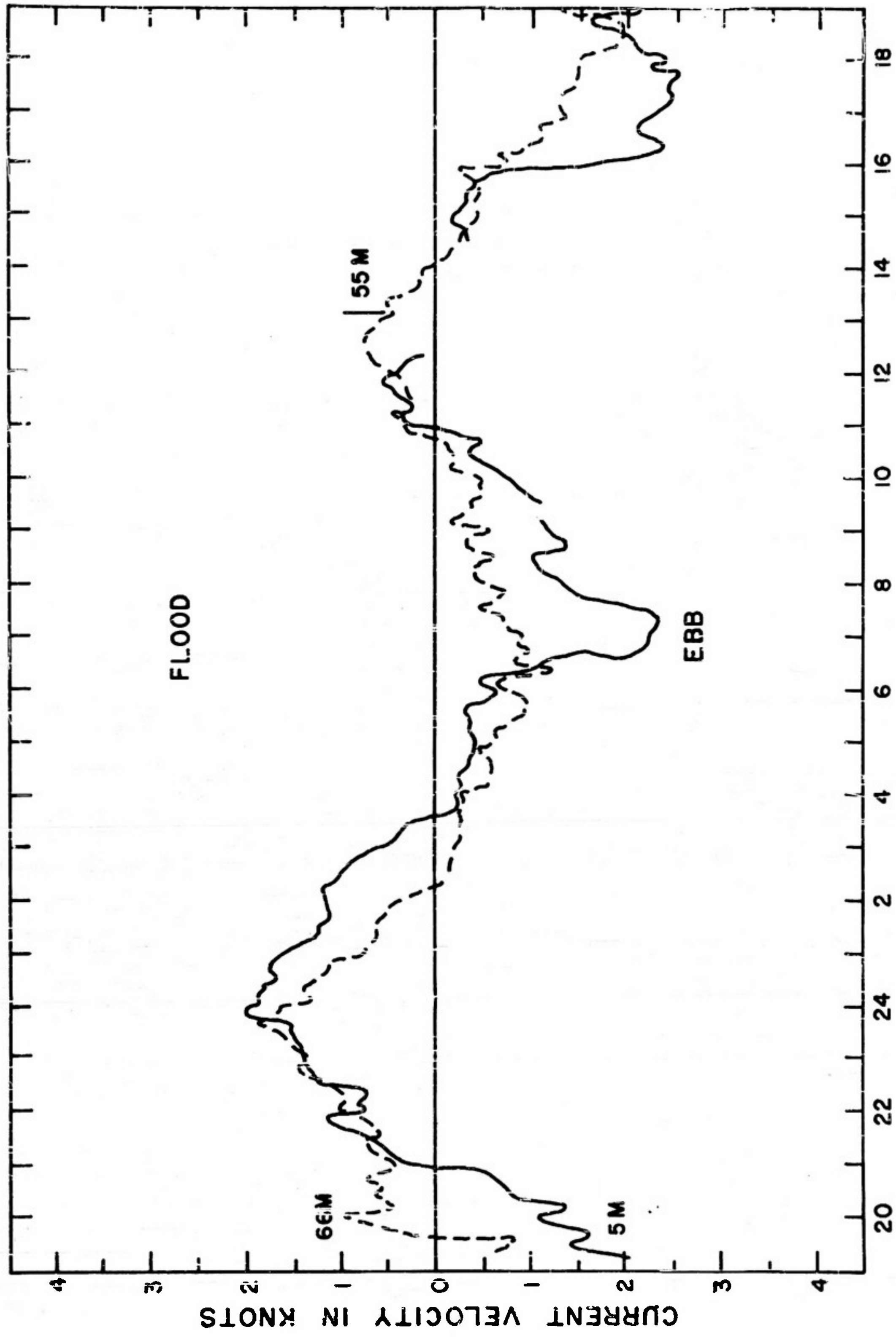
Surface tidal current curve for Admiralty Inlet showing effect of moon's phase, declination, and parallax for May 1947.

Fig. 10-4



Relation of tide at Port Townsend and current in Admiralty Inlet.

Fig. 10-5



Admiralty Inlet currents at two different depths for the position Lat. 47°59.0' N., Long. 122°37.2' W.

Fig. 10-6

VERTICAL DISTRIBUTION OF CURRENTS

In order to determine vertical distribution of tidal currents, measurements have been made in recent years at several depths, both in those regions with the higher current velocities (Paquette and Barnes 1951) and in regions with more nearly average current velocities (University of Washington Department of Oceanography 1953). In the later study net currents over a tidal day were obtained for three stations at six depths between the surface and the bottom in approximately 600 feet of water. The stations were located in a line across the Sound ten miles north of Seattle.

The two western stations show the normal net ebb at the surface and net ebb at depth with the depth of no net motion at about 275 feet. The eastern station shows net flood at all depths with slower net flood at the surface and stronger net flood below a depth of 200 feet.

These results can be explained in terms of the net vertical circulation set up by the fresh water runoff into the Sound. This lighter water remains in the surface layer and must on the average flow seaward. During its travel it mixes with the underlying salt water and becomes more saline. Thus, in addition to the net flow of water in the surface layer there is also a net flow of salt seaward which must be balanced by a net inflow of salt at the deeper levels. This net circulation must be maintained by the surface slope and the existing density structure.

PRESENT STUDIES

The Coast and Geodetic Survey has recently completed a tidal current survey in Puget Sound, including Admiralty Inlet and Skagit Bay. A series of observations made with radio current meters at 49 stations will supplement previous observations with a view to providing characteristic data for the various parts of the Sound. The series of observations at each station varied from 2 to 29 days while most of the stations were occupied for 4 days or more.

Further tidal current surveys in Puget Sound are not contemplated at this time (U.S. Department of Commerce Coast and Geodetic Survey 1953b).

WIND WAVES

INTRODUCTION

Waves in Puget Sound are generated by the local winds. Swell from the ocean and the Strait of Juan de Fuca rarely penetrates any appreciable distance into Admiralty Inlet. The occurrence and size of large waves depends on the occurrence and strength of storm winds and on the lengths of the fetches in the area. The winds almost always blow either up or down the main channels of the Sound. The maximum fetch lengths are 35 nautical miles in the main basin and 30 nautical miles in Hood Canal and Dabob Bay. In places where waves meet opposing tidal currents a choppy cross sea is often set up.

WAVE OBSERVATIONS

In general, waves in Puget Sound are seldom a problem except to the small boat operator. Brough, in connection with the maintenance of railway tracks and road beds along the shore of Puget Sound writes in part:

> There are times during periods of high tides and strong winds when the sea wall becomes damaged by wave action resulting in displacing some of the top courses of the rock, and, during very severe storms, and waves break over the sea wall and the back-wash of water carries away the fines in the nature of ballast and fill material of the underlying track embankment.
>
> It is not often that the sea wall suffers structural damage during ordinary storms and maintenance of the wall is not very much of a problem. However, the washing away of the ballast as it occurs at spotted points is not a condition typical of other track that is not subjected to the heavy washing. Therefore, more than ordinary maintenance is required along the sea wall in order to keep the track in first class and safe condition.
>
> (Great Northern Railway Company 1952.)

Experience in the operation of the Department of Oceanography's research vessels indicates that in the stronger winter storms, waves of 4 foot height can be expected in the water of the main Puget Sound basin, Hood Canal, and Admiralty Inlet. The largest waves observed were in Dabob Bay with a maximum height of 8 feet.

Effect of Ships' Wakes on Shore Installations

The supervision of this problem falls to the U.S. Army Corps of Engineers who report that no study has been made on the effect of ships' wakes on shore

installations. With the exception of the establishment of regulations governing the speed of vessels in the Lake Washington Ship Canal to reduce erosion, damage to shore installations, and to lessen the possibility of accidents, no regulations have been prescribed for this area directed at reducing the damage caused by ships' wakes (U.S. Army Corps of Engineers 1952).

WIND WAVE PREDICTION

Wind data is not published in a form suitable for a statistical study of wind wave production, and thus it is necessary to refer to original records for the required information. For this purpose, winter of 1950 was chosen as a typical example, as records obtained by the Department of Meteorology at the University of Washington were available for that period (University of Washington Department of Meteorology n.d.). Since the mean wind velocities for January and February are somewhat less than 10 knots, all periods with average winds above this value were considered periods of high winds caused by the passage of storm centers. In the two months there were 26 such periods with durations from 1 to 28 hours. The durations fell into three groups:

Short: the length of time of high winds appeared to be more or less uniformly spread over durations up to 7 or 8 hours with ten cases falling in this group;

13 hour: ten cases of high wind had durations between 10 and 15 hours;

25 hour: six cases of high wind had durations between 21 and 28 hours.

In general, the wind did not remain above 10 knots for the total duration, but intervals of higher winds were separated by those of lesser winds. For example, half and three-quarters of the instances of hourly averages above 10 knots were for less than 3 and 6 hours, respectively. There were 20 cases with average hourly velocities above 15 knots, half of less than 2 hours duration; and 3 cases of average hourly winds above 20 knots, one each for 1, 2, and 3 hour durations. In the beginning of April winds of 10 knots or more blew for 41 consecutive hours, with four periods of about 5 hours duration, each with winds over 15 knots, and one 4 hour period with winds over 20 knots.

Theoretical Wave Heights

Table 10-5 has been constructed from procedures found in H. O. Pub. no. 604 (U.S. Navy Hydrographic Office 1951) to utilize the above type of wind data in determining the resulting wave characteristics in Puget Sound.

Since the buildup of winds to 10 or 15 knots is usually rather gradual, the waves have a chance to reach their maximum height as determined by the fetch in all but the very shortest storms. That is, on the weaker storms, waves of 2 to 3 foot height, about 3 second period, and 46 foot distance between crests, are to be expected at the ends of the longer fetches, but with decreased magnitudes for the shorter fetches according to the limits shown in the table. Several times a month the wind will be over 15 knots long enough to produce waves of about 4 foot height (3 1/2 second period and 62 foot wave length) as observed during oceanographic cruises. A few times a year the wind may remain above 20 knots for sufficient time to give waves of 5 or 6 foot amplitude, but only rarely will waves larger than this be observed. The maximum observed wave heights (8 feet in Dabob Bay) must have been due to several hours of wind at 25 knots or more which rarely occur in the Puget Sound region.

THE TABLE. Consider wind with an average velocity of 15 knots beginning to blow in Hood Canal. Waves are to be observed at a point 10 miles from the upwind end of the fetch. Entering Table 10-5 in the 15 knot column, it is found that the waves, after 1 hour, would have a height of 1 1/4 feet, period of 1 2/3 seconds, and wave length of 14 feet. They would continue to grow until they reached a height of 2 3/4 feet, period of 2 1/2 seconds, and a wave length of 32 feet after a total of 3 1/2 hours. They would not increase further since they are shown to be limited by the 10 mile fetch.

PRESENT STUDIES

No known work is in progress on waves in Puget Sound although wind observations are being taken continuously by both the Department of Meteorology on the University of Washington Campus and the U.S. Weather Bureau in Seattle. See section on Climatology for discussion.

TABLE 10-5. Height, Period, and Length of Waves for Various Fetches, Wind Velocities, and Durations in Puget Sound.

DURATION OF WIND [Hours]	WIND VELOCITY [Knots] 10			15			20			25			FETCH OF WIND [Miles]
	WAVE [height and length in feet, period in seconds]												
	Height	Period	Length	Height	Period	Length	Height	Period	Length	Height	Period	Length	
1	1	1 1/4	8	1 1/4	1 2/3	14	1 3/4	2	20	2 1/3	2 1/3	28	
2	1 1/4	1 1/2	12	2	2	20	3	2 1/2	32	4	2 3/4	39	
2 2/3										4 3/4	3	36	
											10 miles		10
3	1 1/2	1 3/4	16	2 2/3	2 1/4	26	4	2 3/4	39	5 1/3	3 1/4	54	
								10 miles					
3 1/2				2 3/4	2 1/2	32							
					10 miles								
4	1 3/4	2	20	3	2 1/2	32	4 3/4	3	46	6 1/2	3 1/2	62	
4 1/4	1 3/4	2	20										
		10 miles											
4 2/3										7	3 3/4	72	
											20 miles		20
5	1 3/4	2 1/3	28	3 1/3	2 3/4	39	5 1/4	3 1/3	57	7 1/3	3 3/4	72	
5 1/4							5 1/3	3 1/3	27				
								20 miles					
6	1 3/4	2 2/3	37	3 1/2	3	46	5 1/2	3 1/2	62	8	4	82	
					20 miles								
6 1/3										8	4 1/4	93	
											30 miles		30
7	2	3	46	3 2/3	3 1/4	54	6	3 3/4	72	8 1/2	4 1/3	96	
								30 miles			35 miles		35
7 1/4	2	3	46										
		20 miles											
7 3/4							6	4	82				
								35 miles					
8	2	3	46	3 3/4	3 1/3	57							
					30 miles								
9	2	3	46	4	3 1/2	62							
					35 miles								
9 2/3	2	3	46										
		30 miles											
10 1/4	2	3	46										
		35 miles											

TRANSPARENCY

INTRODUCTION

The penetration of light into the waters of Puget Sound has been studied by the use of photoelectric or photronic cells. Emphasis has been placed upon the penetration of certain spectral bands of visible solar radiation. No Secchi disc observations have been recorded from the area.

The most pertinent of the available data are described below. Additional information, contained in references cited in the bibliography, include data for the Strait of Juan de Fuca, the waters adjacent to the San Juan Islands, and the open ocean extending northward to Alaska.

AVAILABLE DATA

Observations collected at approximately monthly intervals during 1934 at two stations, one off Pillar Point (lat. 48°18' N., long. 124°53' W.) in the Strait of Juan de Fuca, and the second in the entrance to Hood Canal (lat. 47°56' N., long. 122°38' W.), are published in Seasonal Changes in Components of Submarine Daylight (Williams and Utterback 1935). Similar data for the years 1935 and 1936 for the Pillar Point station and, for the same period, for a station off Point No Point (lat. 47°54' N., long. 122°29' W.) are published in Variations in Components of Submarine Daylight for 1935 and 1936 (Utterback and Miller 1937).

All the data are based on measurements of the penetration of sunlight and were made with a photronic cell fitted with a series of filters that permitted observations to be made at a number of depths for light intensities in relatively narrow spectral bands. In analysing the data the authors have ascribed specific wave lengths in these filters. The results are presented in the form of extinction coefficients $\varkappa$. The term $\varkappa$ is defined by the expression:

$$\varkappa_{\lambda} = 2.30(\log I_{\lambda,z} - \log I_{\lambda,(z+1)})$$

where $I_{\lambda,z}$ and $I_{\lambda,(z+1)}$ represent the light intensities for the ascribed wave length, λ, on horizontal surfaces at the depths z and (z+1) meters, respectively. The data are given in Tables 10-6, 10-7 and 10-8 for various wave length for two depth intervals, 0 to 10 meters, and 10 to 20 meters. The extinction coefficient values $\varkappa$, given in these tables, can be converted to equivalent Secchi disc readings for a depth D, in feet, by means of the following approximate expression:

$$D, \text{(feet)} = \frac{5.6}{\varkappa}$$

(Poole and Atkins 1930).

Transparency at Different Wavelengths

Representative data from the area were used in The Oceans (Sverdrup, Johnson, and Fleming 1946) as examples of the transparency conditions in coastal waters (for example, Fig. 20). A similar presentation of the data for Point No Point is given in Fig. 10-7. Here, observations for 1935 and 1936 for the surface layers, 0 to 10 meters, have been plotted against wavelength. Although the points show wide distribution, the maximum transmission is in the green (between 5000A, and 5500A). This is characteristic of coastal waters. Values for the depth of visibility of a Secchi disc, computed from the relationship $D = 5.6/\kappa$, are shown for $\lambda = 5300$A. in the tables.

Data for the depth interval, 0-10 meters for $\lambda = 5300$A., are plotted against the months of the year in Fig. 10-8. A wide spread in the values for any one month may be observed and, in general, the observations from Point No Point reveal a lower transparency than those from Pillar Point. There is no clearly defined seasonal pattern although the data indicate that optimal transparencies occur in the fall months. Comparison of the data in Figs. 10-7 and 10-8 with material in The Oceans (Sverdrup, Johnson, and Fleming 1946) shows that the transparencies vary between those for "coastal maximum" and "oceanic minimum."

FACTORS AFFECTING TRANSPARENCY

The low transparency in the area may be ascribed to the suspended materials and dissolved humic compounds introduced by fresh water runoff from the land, and to the presence, at certain times, of large plankton populations. Heavy rains, particularly in the fall, increase the quantities of silt and suspended load of the rivers. Muddy outflow can easily be traced into Puget Sound (see section on Geology: Recent Sedimentation). The large amount of terrigenous material carried into Puget Sound by the rivers undoubtedly contributes to reduced transparencies. The period of heavy runoff extends through the spring and summer in the major rivers by the melting snow at the higher elevations (see section on Hydrology). During the spring and summer large plankton populations must also play their part.

The period of optimal transparencies is in the fall corresponding to months with minimum runoff, small plankton populations, and greatest oceanic influence in the area. A qualitative agreement exists between transparency and salinity. At Point No Point all low transparencies (large values of κ) occurred when salinities were less than $29^{\circ}/oo$.

The causes of the reduced transparencies and the nature of the water movements in Puget Sound are such that the conditions at Point No Point cannot be considered as representative of the whole Sound. Data from the entrance to Hood Canal are essentially similar to those for Point No Point as might be expected from the close proximity of the two stations. Transparencies

TABLE 10-6. Absorption Coefficients at Pillar Point, 1934.

DATE	λ=4600A. Depth*		λ=4800A. Depth		λ=5150A. Depth		λ=5300A. Depth		Equiv. Secchi Disc Depth**		λ=5650A. Depth		λ=6000A. Depth	
	0-10	10-20	0-10	10-20	0-10	10-20	0-10	10-20	0-10	10-20	0-10	10-20	0-10	10-20
1 4 34	---	---	---	---	---	---	0.205	0.094	27	60	0.255	0.118	0.400	---
1 27 34	0.193	0.217	0.145	0.184	0.130	0.163	.119	.161	47	35	.166	.184	.351	0.312
3 4 34	.236	.171	.208	.168	.192	.142	.182	.142	31	39	.229	.161	.422	.315
3 30 34	.309	---	.232	.270	.197	.288[1]	.197	.224	28	25	.268	.213	.414	.354
4 28 34	.308	.177	.279	.149	.216	.165	.288	.149	25	38	.273	.169	.439	.275
6 3 34	.513	---	.456	---	.392	.236[1]	.331	.238[1]	17	24	.365	.238[1]	.506	.400
7 2 34	.212	.159	.184	.144	.166	.129	.169	.131	33	43	.224	.159	.406	.265
7 21 34	---	---	---	.132	---	.224	---	.195	--	29	---	.224	---	---
11 10 34	.218	.206[1]	.224	.173	.184	.155	.167	.165	34	34	.238	.181	.368	---
12 15 34	.200	.150	.164	.131	---	.084	.150	.092	37	61	.244	.155	.397	.139

* Depth in meters.

** Depth in feet.

[1] 10-15 meters only.

Note: λ = wavelength in Angstrom units.

4500A. to 5000A. = Blue

5000A. to 5700A. = Green

5900A. to 6100A. = Orange

Longer than 6100A. = Red

Table from Seasonal Changes in Components of Submarine Daylight (Williams and Utterback 1935).

TABLE 10-7. Extinction Coefficients Per Meter at Pillar Point, 1935-36.

DATE	λ =4600A. Depth*		λ =4800A. Depth		λ =5150A. Depth		λ =5300A. Depth		Equiv. Secchi Disc Depth**		λ =5650A. Depth		λ =6000A. Depth		λ =6600A. Depth	
	0-10	10-20	0-10	10-20	0-10	10-20	0-10	10-20	0-10	10-20	0-10	10-20	0-10	10-20	0-10	10-20
2 9 35	0.154	0.239	0.153	0.223	0.129	0.170	0.120	0.179	47	31	0.184	0.197	0.359	0.310[1]	0.638[2]	---
3 16 35	.241	.149	.223	.188	.190	.149	.210	.141	27	40	.257	.159	.410	.328	.492	---
4 20 35	.295	.147	.245	.118	.238	.158	.236	.131	24	33	.344	.147	.457	.364	.484	---
5 25 35	.216	.210	.206	.182	.189	.164	.176	.184	32	30	.241	.201	.394	.355	.570	---
6 23 35	.230	.201	.221	.092	.151	.167	.212	.081	26	69	.223	.141	.360	.309	.698[2]	---
7 25 35	.260	.227	.246	.174	.219	.134	.219	.122	26	46	.257	.163	.396	.225	.446	---
9 13 35	.447	.168[1]	.267	.081[1]	.200	.146[1]	.205	.146[1]	27	38	.232	.146[1]	.296	.293	.698[2]	---
11 10 35	.147	.126	.120	.119	.108	.104	.112	.109	50	51	.195	.102	.357	.318	.455	---
12 7 35	.147	.149	.115	.132	.108	.144	.120	.112	47	50	.183	.184	.327	.304	.454	---
1 18 36	.220	---	.238	.250[1]	.236	.202[1]	.219	.170[1]	26	33	.319	.208[1]	.443	---	.622	---
2 22 36	.260	.156	.167	.163	.162	.112	.140	.119	40	47	.196	.144	.392	.289	.483	---
3 23 36	.161	.145	.141	.112	.128	.120	.133	.111	42	50	.189	.170	.333	.241	.374	---
4 25 36	.188	.144	.171	.138	.151	.128	.171	.121	33	46	.210	.162	.381	.393	.798[2]	---
5 23 36	.213	.204	.199	.206	.162	.176	.146	.173	38	32	.202	.202	.366	.316	.522	0.416[1]
7 14 36	.179	.128	.161	.109	.129	.113	.113	.113	50	50	.185	.133	.507	.161	.560	---
8 22 36	.385	---	.318	.304	.299	.332	.215	.315	26	18	.272	.285	.437	---	.570	---
9 18 36	.144	.120	.133	.093	.097	.083	.088	.077	64	73	.095	.079	.246	.267	.510	---
10 31 36	.157	.106	.131	.092	.112	.065	.119	.067	47	84	.123	.074	.323	.256	.421	0.390[1]
12 5 36	.140	.132	.120	.102	.099	.093	.107	.100	52	56	.110	.108	.322	.295	.348	---

* Depth in meters.
** Depth in feet.
[1] 10-5 meters only.
[2] 0-5 meters only.

Note: λ = wavelength in Angstrom units.
4500A. to 5000A. = Blue
5000A. to 5700A. = Green
5900A. to 6100A. = Orange
Longer than 6100A. = Red

Table from Variations in Components of Submarine Daylight for 1935 and 1936 (Utterback and Miller 1937).

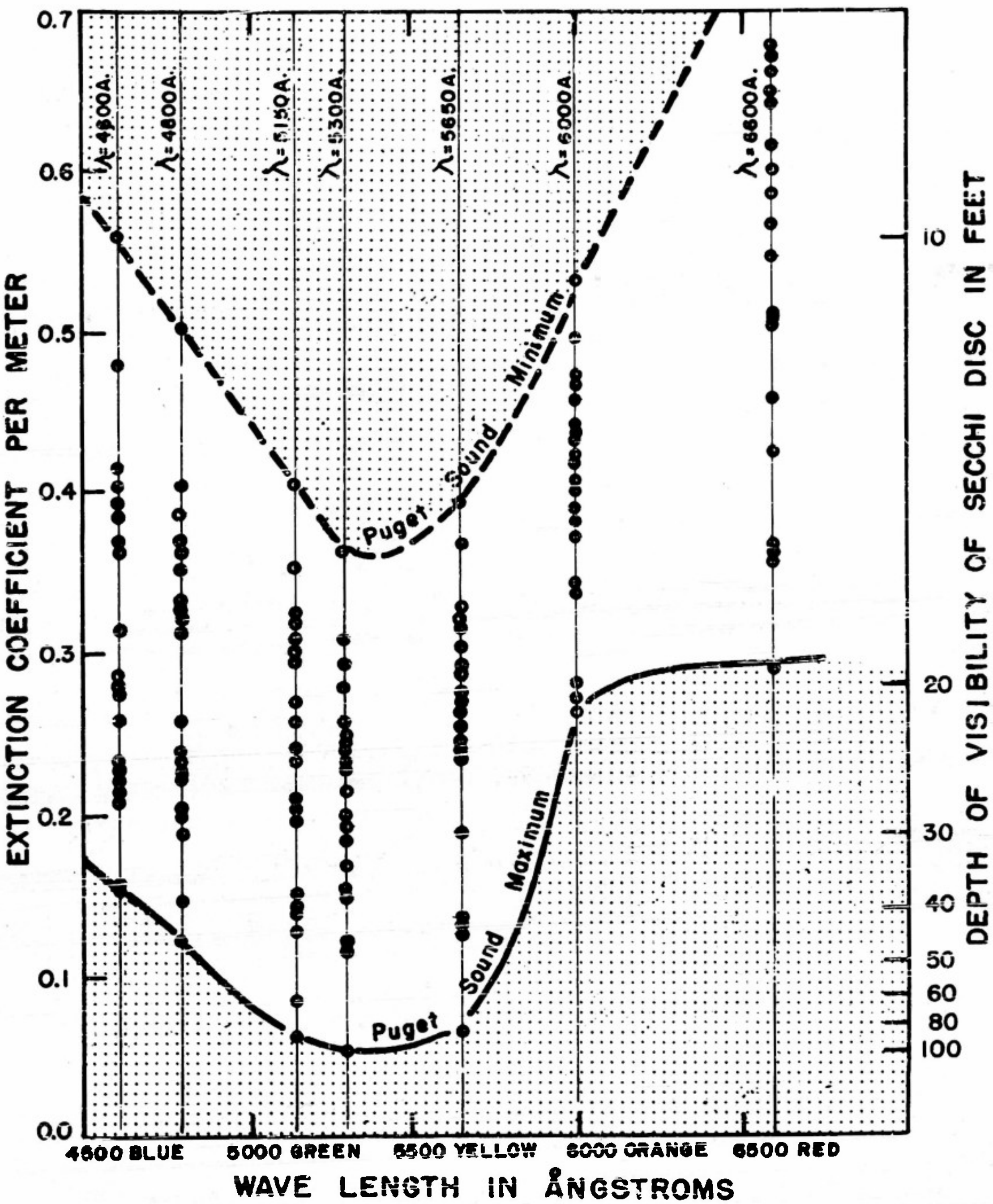
TABLE 10-8. Extinction Coefficients Per Meter at Point No Point, 1935-36.

DATE	λ=4600A. Depth*		λ=4800A. Depth		λ=5150A. Depth		λ=5300A. Depth		Equiv. Secchi Disc Depth**		λ=5650A. Depth		λ=6000A. Depth		λ=6600A. Depth	
	0-10	10-20	0-10	10-20	0-10	10-20	0-10	10-20	0-10	10-20	0-10	10-20	0-10	10-20	0-10	10-20
2 10 35	0.389	0.110	0.365	0.155	0.296	0.188	0.257	0.188	22	30	0.292	0.198	0.443	0.230	0.510	---
3 17 35	.365	.170	.313	.173	.271	.356	.245	.211	23	27	.368	.154	.417	.274	.680[2]	---
4 21 35	.259	.201	.226	.184	.195	.153	.184	.139	30	40	.239	.184	.391	.296	.570	---
5 26 35	.228	.337	.387	.277	.325	.237	.294	.206	19	27	.316	.239	.472	.343	.650	---
6 24 35	.366	.233	.331	.230	.259	.228	.227	.204	25	27	.270	.212	.422	.350	.645	---
7 28 35	.415	.278[1]	.331	.340[1]	.317	.286[1]	.279	.222	20	25	.304	.203	.443	.394[1]	.602	
9 14 35	.214	.230	.222	.208	.142	.168	.170	.131	33	33	.246	.075	.337	.466[1]	.291	---
11 9 35	.152	.210	.146[2]	.166	.085	.140	.120[2]	.126	47	44	.127	.133	.382	.281	.363	---
12 8 35	.207	.208	.203	.157	.127	.193	.153	.147	37	38	.191	.194	.378	.322	.680[2]	
1 19 36	.275	.110	.238	.184	.233	.161	.197	.271	28	21	.263	.148	.384	---	.361	---
2 23 36	.314	---	.232	.161	.204	.188	.197	.132	28	42	.256	.144	.402	---	.366	---
3 24 36	.279	.277	.258	.254	.205	.225	.216	.201	26	28	.239	.248	.474	.318	.662	---
4 26 36	.386	.300	.322	.295	.309	.204	.247	.246	23	23	.328	.207	.458	.403	.617	---
5 24 36	.559	.110	.503	.210	.406	.234	.362	.232	15	24	.397	.248	.498	.443	.713	---
6 24 36	.285	.250	.351	.170	.242	.222	.231	.240	24	23	.289	.254	.403	.318	.547	0.416[1]
7 20 36	.480	---	.405	.374[1]	.352	.277	.310	.252	18	22	.328	.282	.534	.496[1]	.826[2]	---
8 21 36	.405	.416[1]	.370	.256	.304	.212	.248	.212	23	26	.276	.217	.434	.460[1]	.586	---
9 19 36	.229	.229	.188	.202	.142	.143	.118	.132	47	42	.127	.113	.272	.316	.511	.440[1]
11 1 36	.157	.253	.122	.233	.062	.194	.054	.183	104	31	.067	.163	.265	.376	.428	---
12 6 36	.224	.171	.203	.151	.150	.129	.154	.115	36	48	.134	.128	.341	.295	.459	---

* Depth in meters.
** Depth in feet.
[1] 10-15 meters only.
[2] 0-5 meters only.

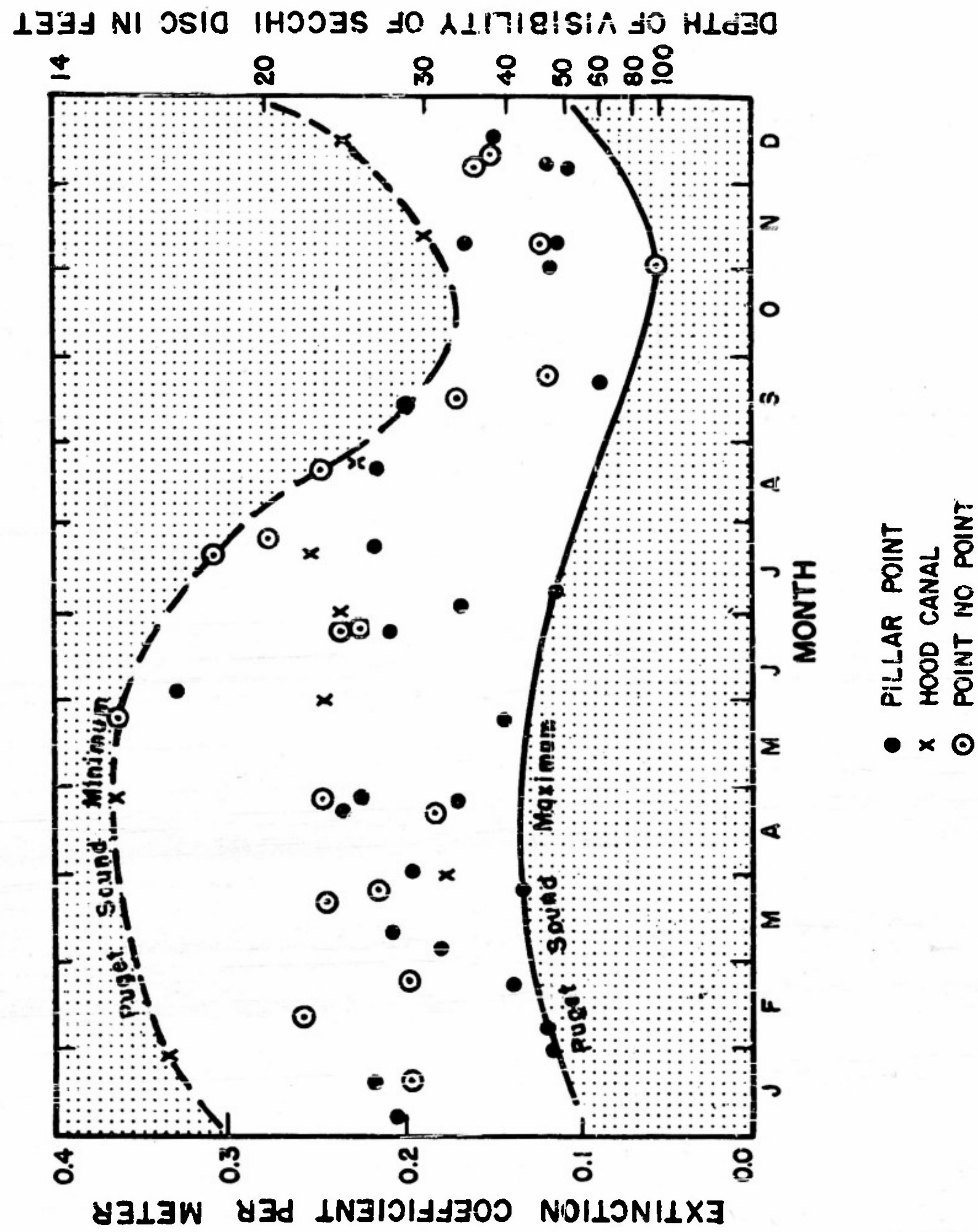
Note: λ = wavelength in Angstrom units.
4500A. to 5000A. = Blue
5000A. to 5700A. = Green
5900A. to 6100A. = Orange
Longer than 6100A. = Red

Table from Variations in Components of Submarine Daylight for 1935 and 1936 (Utterback and Miller 1937).



Extinction coefficients off Point No Point, 1935-36, for wavelengths indicated. Plotted points represent the 0-10 meter interval values found in Table 10-7.

Fig. 10-7



Seasonal variation of extinction coefficients for wavelength 5300A. for Pillar Point, 1934-36; Hood Canal, 1934; and Point No Point, 1935-36. Plotted points represent averaged 0-10 meter interval values found in references (Williams and Utterback 1935; Utterback and Miller 1937) and reproduced in part in Tables 10-5, 10-6, and 10-7.

Fig. 10-8

at Pillar Point are generally greater than those at the other two stations because of the reduced influence of local runoff and the closer source of inflowing oceanic water.

Comparison of the data for the two depth intervals, 0 to 10 meters, and 10 to 20 meters, shows that in 75 percent of the cases the transparencies near the surface were less than at depth. In the 25 percent of the cases where the surface layers were more transparent, the differences in the extinction coefficients were very small. Recent preliminary observations made by the Department of Oceanography with a hydrophotometer have shown that the surface layer of reduced transparency can be only a few meters thick, corresponding to the zone of marked dilution. No detailed studies of the vertical variations in transparency have been published for Puget Sound although some information for adjacent areas may be found in the references (Utterback and Boyle 1933; Utterback 1933; Utterback and Jorgensen 1934).

A patchy distribution can be anticipated at any given time and continuous observations at any one locality can be expected to show varying transparencies. Fluctuations related to the tidal currents are probable.

REFLECTION AND SCATTERING

Basic investigations of the amount of sunlight reflected and scattered by the sea surface have been made for different sky conditions and sea states (Trumble 1947). Studies have also been made of light scattering in the water (Jorgensen 1938).

COLOR OF THE WATER

No detailed observations are available concerning the apparent color of the surface waters of Puget Sound. It generally varies between green and brown, depending upon the content of suspended and dissolved material. Discoloration caused by tremendous concentrations of planktonic organisms has been observed. See Biology Section.

PRESENT STUDIES

No new work is known to be in progress.

WATER MASS CHARACTERISITCS

INTRODUCTION

Salinity and temperature observations in the waters of Puget Sound and approaches have been made rather extensively since 1932--the years 1942-1947--excluded. The physiography and bathymetry of the basin, the local climate, and the contributing sources of fresh and salt water influence these water mass characteristics. The principal circulating and mixing forces are largely tidal, but wind stress and hydrostatic head from river runoff are also important. Locally, the restricted entrance and subdivision sills, the deflecting force of the earth's rotation and irregular channels, combined with the inertia of the moving water, also influence circulation and mixing. See volume II, section on Hydrography for general bathymetry, the location of the principal sills, and depth-volume relationships.

Overall, the Puget Sound area is one in which precipitation and runoff exceed evaporation--the excess fresh water draining seaward surficially carrying with it a varying amount of salt. A net influx of salt water occurs at depth. The primary source of this salt water is the open Pacific Ocean, but this water is somewhat diluted in the Strait of Juan de Fuca by effluent from the Strait of Georgia and to a lesser extent by that from Puget Sound itself. Mixing occurs predominantly over the shoaling bottom areas in the eastern end of the Strait of Juan de Fuca, and in the connecting channels to the Strait of Georgia and Puget Sound. Puget Sound can be considered essentially a tributary embayment to the Strait of Juan de Fuca-Strait of Georgia system, little affecting what happens in that system, but on the other hand being greatly affected by the conditions existing therein. The Strait of Juan de Fuca is the immediate source of deep water in the Puget Sound Basin. It is the source of salt, although at times, more saline water at basin depths can be replaced by less saline Strait water.

Fresh water is added to Puget Sound by river runoff, ground water, and direct precipitation on the water surface. Fresh water added by condensation of water vapor on the water surface occurs but is negligible compared to the first named sources. The loss of fresh water by evaporation also occurs and is relatively most important from July to early October during the period in which runoff and precipitation are low. See Table 2-3.

The ocean during summer is a pronounced heat sink. At this season the coldest subsurface water of the year penetrates the Strait of Juan de Fuca at depth. Part of this water mixes at the sills with relatively warm and dilute surface water flowing seaward from the inner basins. The resultant mixture feeds landward, generally at or near the bottom. During winter, the water surface loses heat to the atmosphere, the greatest change in temperature occurring in the shallow extremities of the inner basins. The temperature of deeper Strait water, at its yearly maximum in winter, approaches

that of the deep basin water and may at times act as a heat source for that subsurface water as well as for the surface water within the Strait proper. During periods of intense cooling, however, the upper water in the Strait of Juan de Fuca may be greatly cooled locally as well as by influx of cold water from the Strait of Georgia. Consequently the mixed water which flows into Puget Sound at depth is colder than that formed at the surface within the Sound.

The sills are critical in controlling the mixing and the nature of the water contributing to depth in the inner basins of Puget Sound. Replacement of the deep water is effected rather abruptly during the autumn by addition of greater density, high salinity water, and more or less gradually during the remainder of the year by turbulent mixing with less dense water.

SALINITY DISTRIBUTION

On the basis of the general background given, the water mass characteristics will now be discussed. Summer, winter, and general seasonal conditions will be described utilizing the results of recent surveys as typical examples.

Summer Conditions

The summer distribution of salinity in the Puget Sound system from the Strait of Juan de Fuca to the heads of various tributary arms is shown by mid-channel salinity profiles in Fig. 10-9. The field observations were made in the period 18-22 July 1953 on BROWN BEAR cruise no. 30. The salinity at the outermost station in the Strait of Juan de Fuca ranges from 31.7 $^{o}/oo$ at the surface to 33.8 $^{o}/oo$ at the 600 foot depth, and averages approximately 33.2 $^{o}/oo$. It decreases to average values of 29.4 $^{o}/oo$ over approximately the same depth range in Puget Sound south of the Tacoma Narrows, and 30.0 $^{o}/oo$ in Hood Canal. Pronounced drops in salinity, 0.5 $^{o}/oo$ to 1.5 $^{o}/oo$, occur at the major sills, such as those across the main channel from Victoria to Green Point, at Admiralty Inlet, and in the Tacoma Narrows. Similar gradients are evident at Deception Pass and the entrance to Hood Canal. The along-channel gradients are relatively small in the deeper water of the principal basins away from the direct influence of the sills or lateral constrictions.

In the surficial waters, shallow lenses of relatively fresh water appear locally off the river mouths where fresh water from runoff overrides the saline water at depth. Most of the salinity increases in the basins occurs within the upper 50 feet. Over this depth range salinities may increase from a few parts per mille to 27 $^{o}/oo$ or 29 $^{o}/oo$. At greater depths the change is smaller, not more than 1 $^{o}/oo$ to 2 $^{o}/oo$, although the maximum depth may be as much as 900 feet. The clouds of accumulated fresh water discharged by rivers are most prominent in the immediate vicinity of river

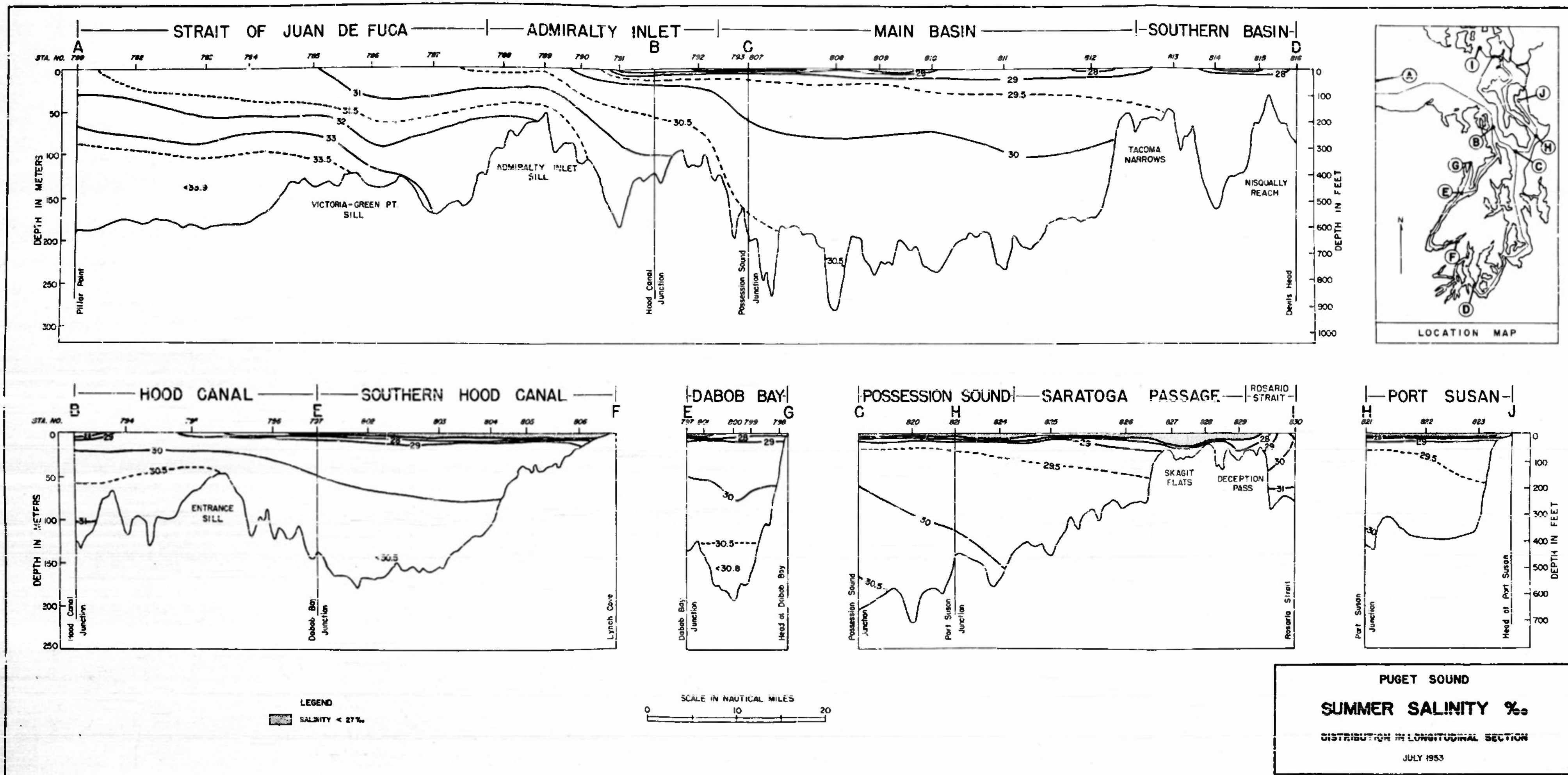

STRAIT OF JUAN DE FUCA
ADMIRALTY INLET
MAIN BASIN
SOUTHERN BASIN
VICTORIA-GREEN PT. SILL
ADMIRALTY INLET SILL
TACOMA NARROWS
NISQUALLY REACH
Pillar Point
Hood Canal Junction
Possession Sound Junction
Devils Head
DEPTH IN METERS
DEPTH IN FEET
STA. NO.
LOCATION MAP
HOOD CANAL
SOUTHERN HOOD CANAL
ENTRANCE SILL
Hood Canal Junction
Dabob Bay Junction
Lynch Cove
DABOB BAY
Head of Dabob Bay
POSSESSION SOUND
SARATOGA PASSAGE
ROSARIO STRAIT
SKAGIT FLATS
DECEPTION PASS
Port Susan Junction
Rosario Strait
PORT SUSAN
Head of Port Susan
LEGEND
SALINITY < 27‰
SCALE IN NAUTICAL MILES
PUGET SOUND
SUMMER SALINITY ‰
DISTRIBUTION IN LONGITUDINAL SECTION
JULY 1953

Fig. 10-9

mouths, but may extend over most of the basin surface inside the entrance sills. Near them lateral vertical turbulence accompanying the tidal currents tends to break down the stratification, affording at times rather thorough top to bottom mixing. Rather thorough mixing is a common occurrence in the Tacoma Narrows and Deception Pass and may possibly occur in Admiralty Inlet accompanying the stronger tidal currents. Figure 10-9 shows a lens of fresh water largely contributed by the Skagit River, but supplemented by the Snohomish, Stillaguamish and lesser rivers, extending over the northern end of Puget Sound from Deception Pass to the middle of the main basin at Alki Point, and also seaward into Admiralty Inlet, there dissipating by vertical turbulence. The contribution of the Puyallup River is evident just north of the Tacoma Narrows and that of the Nisqually River farther to the south. Within the Tacoma Narrows the strong tidal currents have destroyed the stratification.

In Hood Canal the individual effects of the several contributing rivers cannot be readily distinguished in mid-channel, but a surface cloud of less saline water extends continuously from Lynch Cove, in the south, to the region of stronger currents at the entrance. This low salinity layer also extends into Dabob Bay at the northern end of Hood Canal proper.

The dispersion of the surface clouds of less saline water requires vertical or lateral mixing across isopycnic (σ_t) surfaces, with attendent high energy demand. This energy is largely supplied by wind and tide, the tide having the greatest influence in the Puget Sound area. The clouds of less saline water thus tend to maintain their identity--moving bodily with changing wind and tide--but resisting mixing with ambient water of different mass characteristics. Profile measurements made with an S-T-D (Salinity-Temperature-Depth Recorder) have shown salinity gradients along the vertical exceeding 3 $^o/oo$ per foot. Lateral variations at tide rips, where waters of different salinities converge, may amount to a few parts per thousand within a few feet.

The movement of surface lenses of the less saline water has also been studied by using the S-T-D. On a flood tide the hydrostatic head of the fresh water opposes the incoming tidal stream to give a well defined convergence with closely spaced and sharply tilted isolines. With an ebb tide the hydrostatic head of the fresh water is directed along the tidal flow. The boundary between the two water masses is diffuse and the isolines almost horizontal. Fingers of less saline water frequently extend downstream. Aerial photographs of the effluent of the Dosewallips River carrying glacial silt into Hood Canal show distinctly the nature of these interfaces. On an ebb tide the surface water may ride seaward over a mixing sill but retain much of its identity until it is pinched off by the subsequent flood. Thus, clouds of fresh water may be discharged in step with the tide.

Within the Sound a two-layer water structure predominates. In this type of distribution a layer of relatively fresh water overlies water of

salinity approaching that of the open sea, the two layers being separated by a thin interface transition zone. Significant interfaces do occasionally occur at depth, to give a system of three, or very rarely more, significant layers. In particular, stratification may occur at sill level in the deeper sills which separate tributary arms such as Dabob Bay and Port Susan from the main basin. Mixing forces across the sills are small and a small density gradient at sill level may be sufficient to greatly retard the flushing of waters entrapped behind the sills. Interchange of entrapped water has been almost entirely blocked for periods of three months in Port Susan and nine or more months in Dabob Bay. No evidence for isolation extending over a period of several years has been found in Puget Sound waters although it apparently occurs in the deeper waters of certain of the fiords in British Columbia to the north.

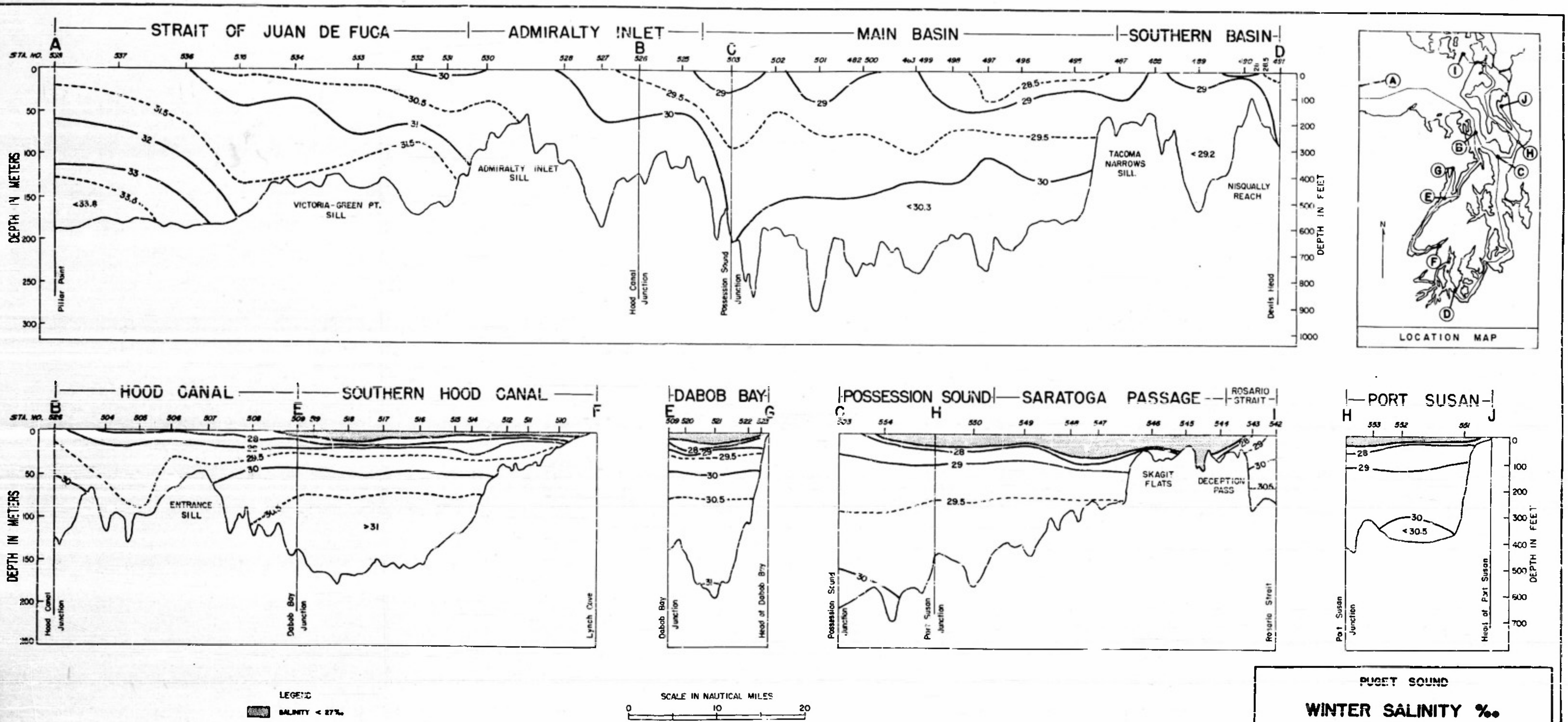
Studies with the S-T-D, which gives continuous vertical profiles, show a stepwise distribution of properties in the head of the Strait of Juan de Fuca. As many as four distinct homogeneous layers, separated by relatively sharp transition interfaces, have been found in a single vertical profile. This structure is attributed to the interleafing, at their respective density levels, of discrete entities of water contributed into the Strait over their respective mixing sills. The isolines depicted in the salinity profiles and diagrams shown in this report are based on conventional reversing bottle techniques, and show the macrostructure but exclude much pertinent small scale structure at depth as observed with the S-T-D.

Winter Conditions

The winter salinity distribution, based on observations made during February 1953, on BROWN BEAR cruise no. 21, is shown in Fig. 10-10. The pattern is similar to that in summer but the near-surface gradients are somewhat less as a consequence of increased wind mixing and the local cooling which promotes convective overturn. At corresponding locations and depths the winter salinity values in the deeper waters do not vary more than 0.0 °/oo to 2.0°/oo. Greater changes at depth occur in the Strait of Juan de Fuca, near the contributing source of deep water from the ocean, than occur in the inner basins. On the other hand the basins, near the contributing source of river water, show greater changes in surface salinity than does the Strait down stream from these fresh water sources. This ocean source changes seasonally with the greatest vertical uplift accompanying the summer wind and current patterns along the coast and feeding the highest salinity and lowest temperature water into the Strait during July and August.

General Seasonal Conditions

The seasonal changes in salinity for the period October 1952 (February 1953 at Pillar Point) to February 1954 are shown for selected locations by the following figures: Fig. 10-11, Pillar Point; Fig. 10-13, Point Jefferson; Fig. 10-14, Gordon Point; Fig. 10-15, Tekiu Point; and Fig. 10-16, Camano Head, East. These patterns are based on the results of monthly cruises made



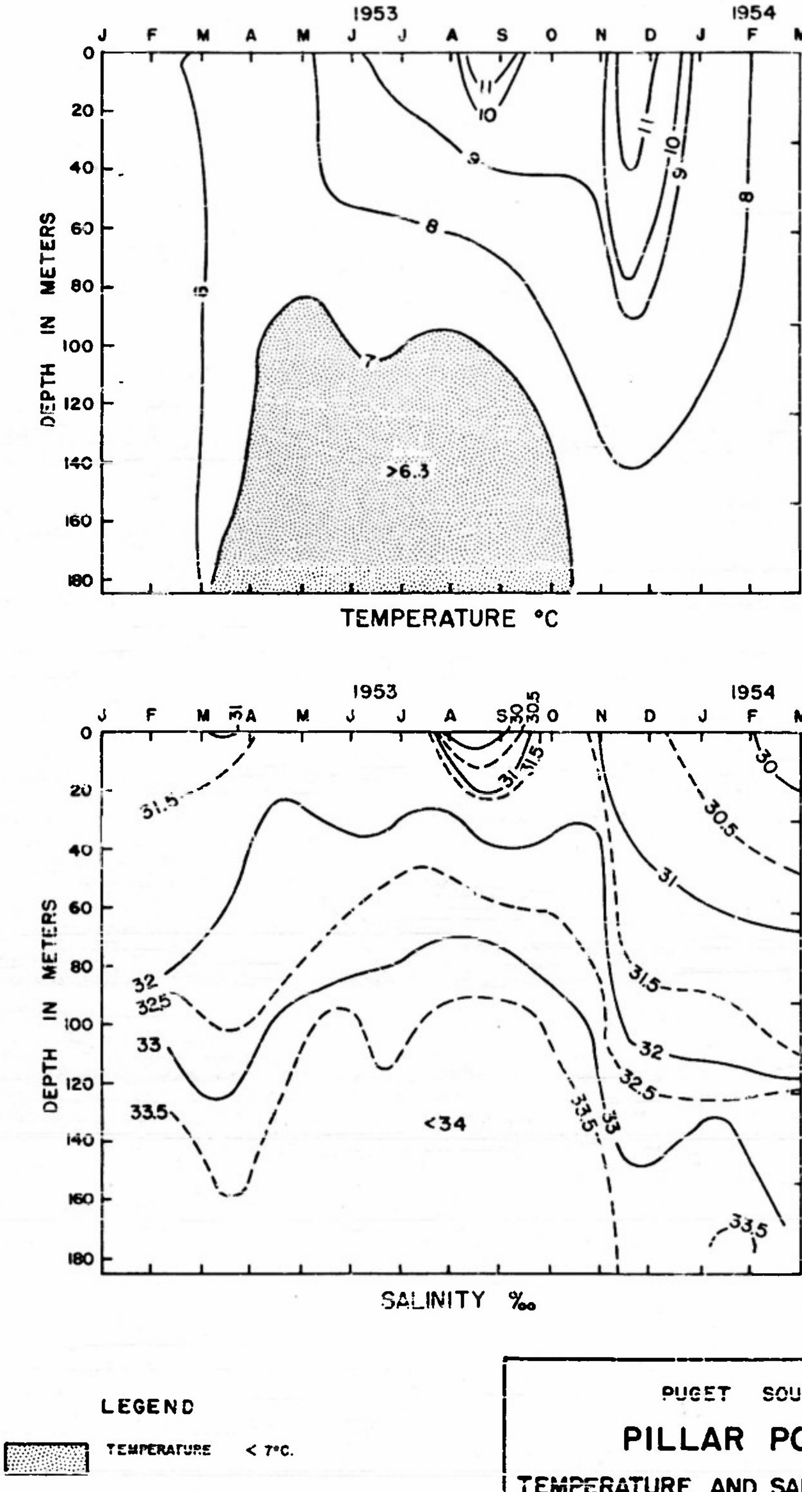
PUGET SOUND

WINTER SALINITY ‰

DISTRIBUTION IN LONGITUDINAL SECTION

FEBRUARY 1953

Fig. 10-10



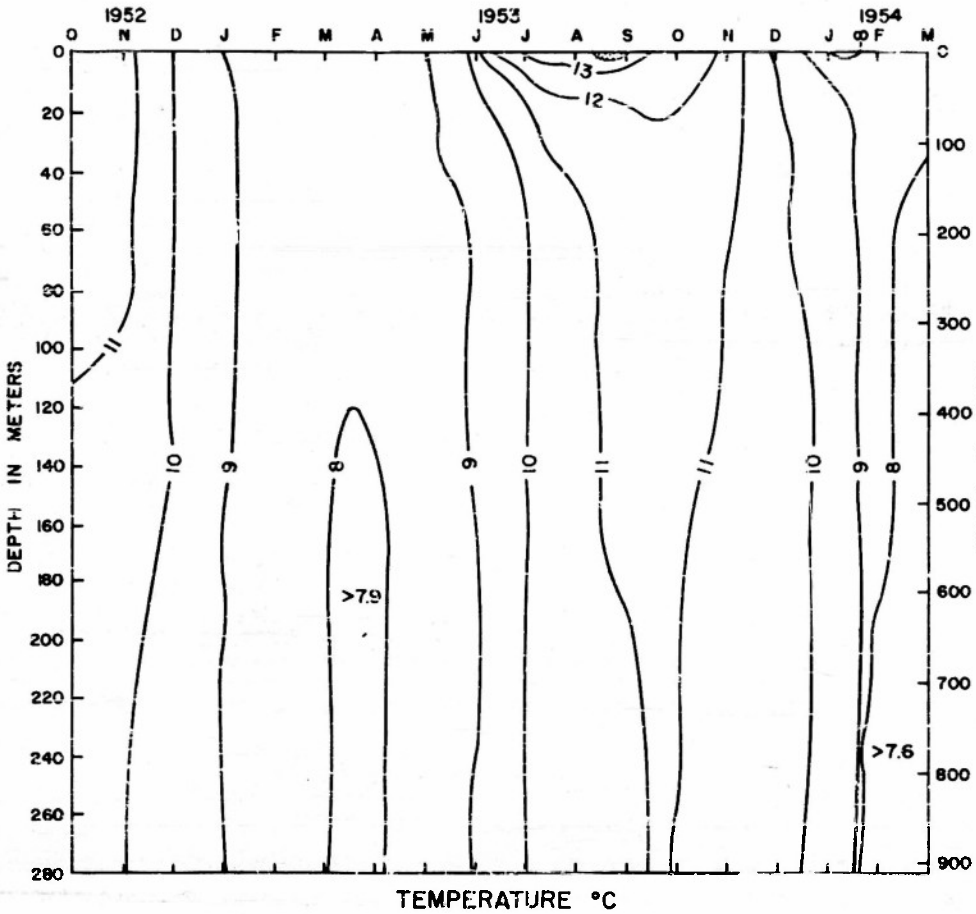
PUGET SOUND

PILLAR POINT

TEMPERATURE AND SALINITY CYCLES

FEBRUARY 1953— MARCH 1954

Fig. 10-11



LEGEND

TEMPERATURE > 14°C.

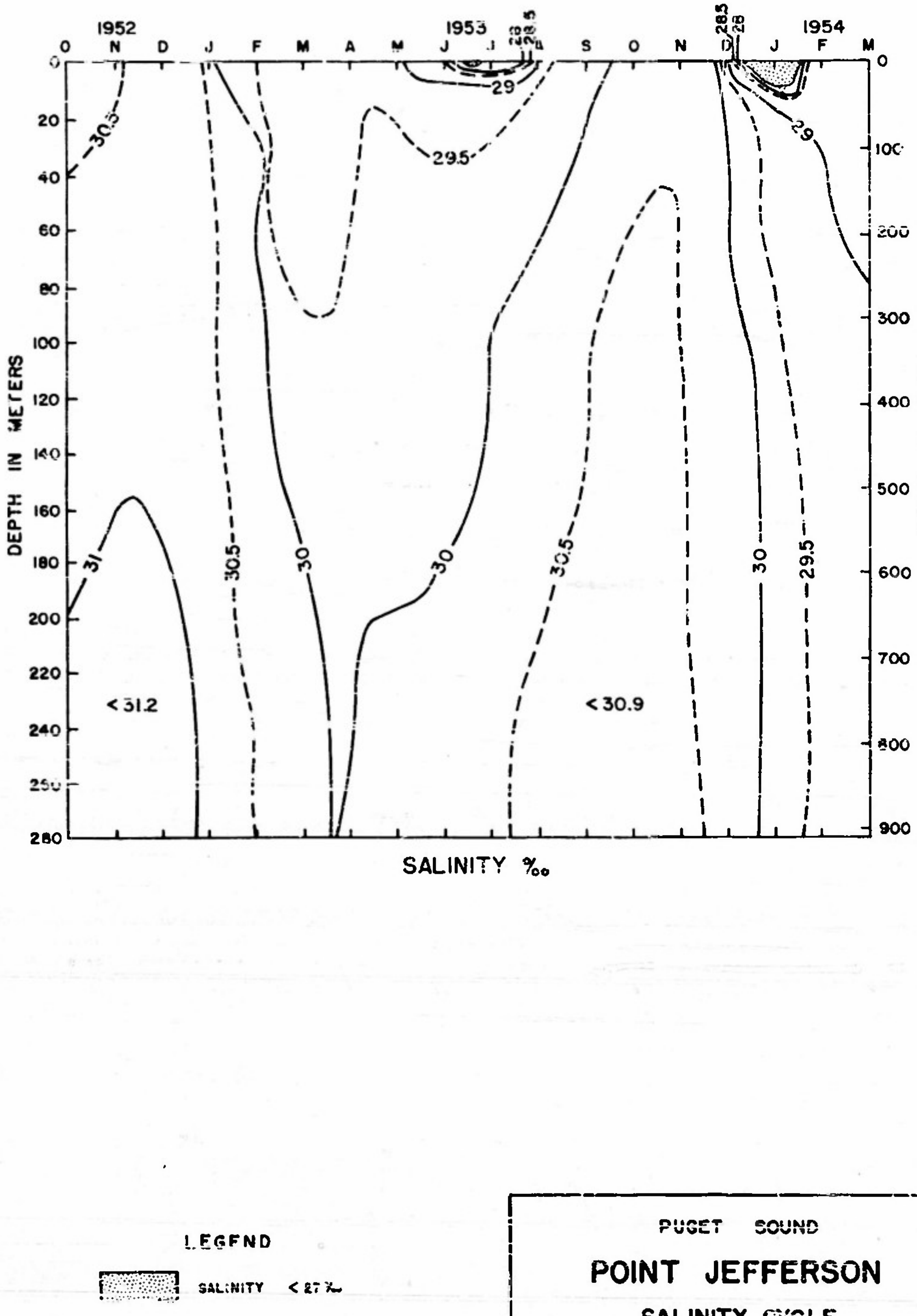
PUGET SOUND

POINT JEFFERSON

TEMPERATURE CYCLE

OCTOBER 1952 — MARCH 1954

Fig. 10-12



PUGET SOUND

POINT JEFFERSON

SALINITY CYCLE

OCTOBER 1952 – MARCH 1954

Fig. 10-13

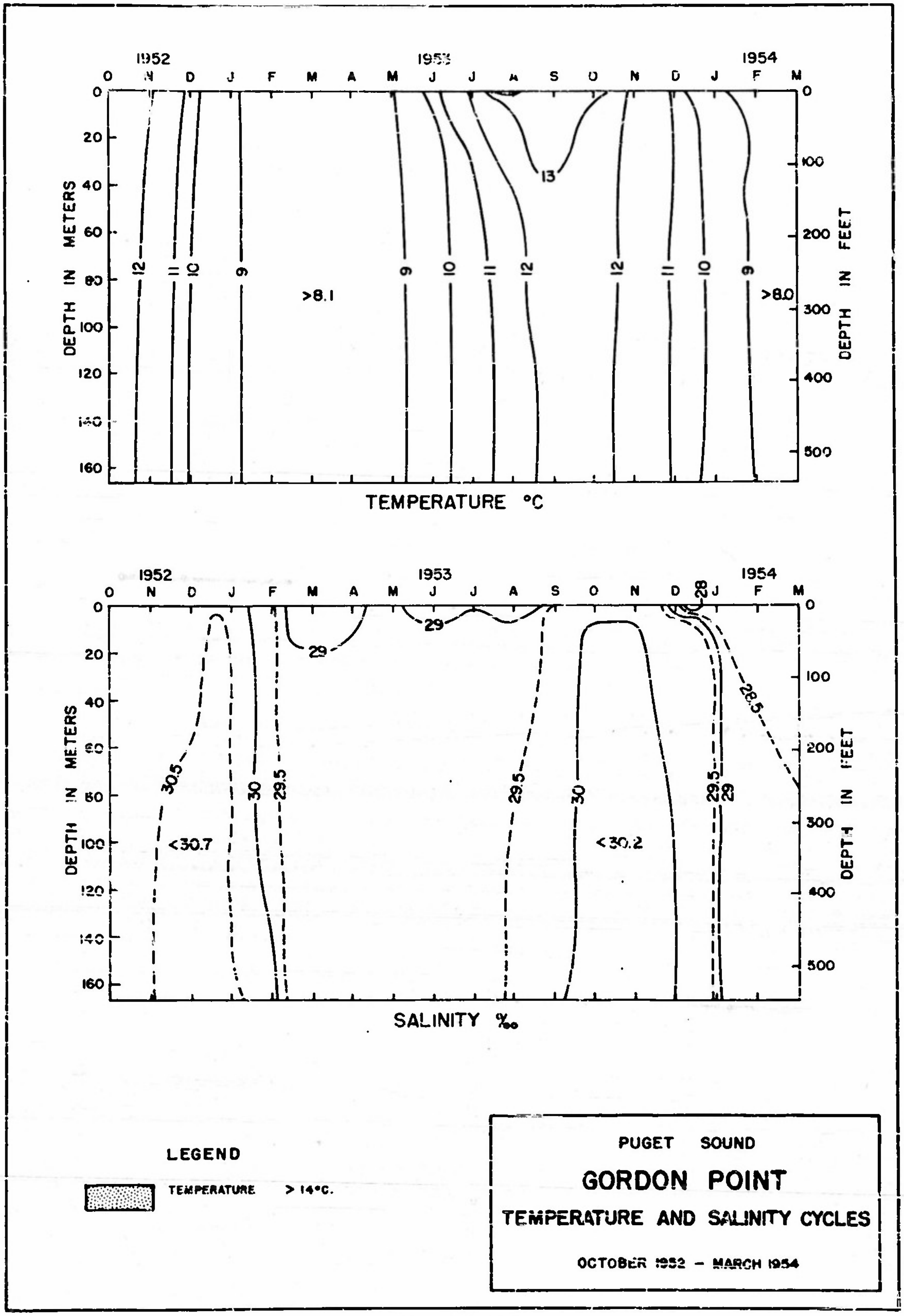
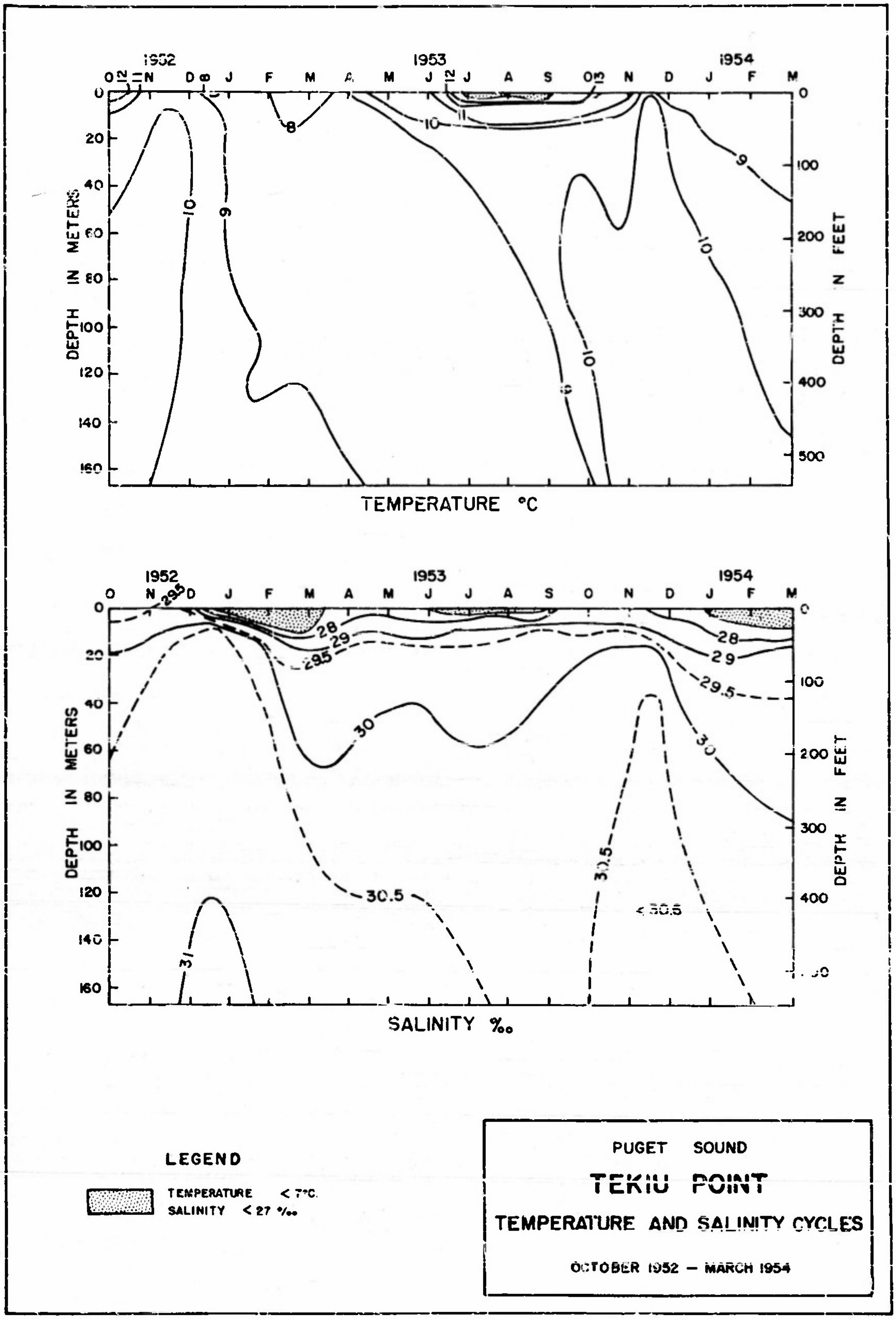
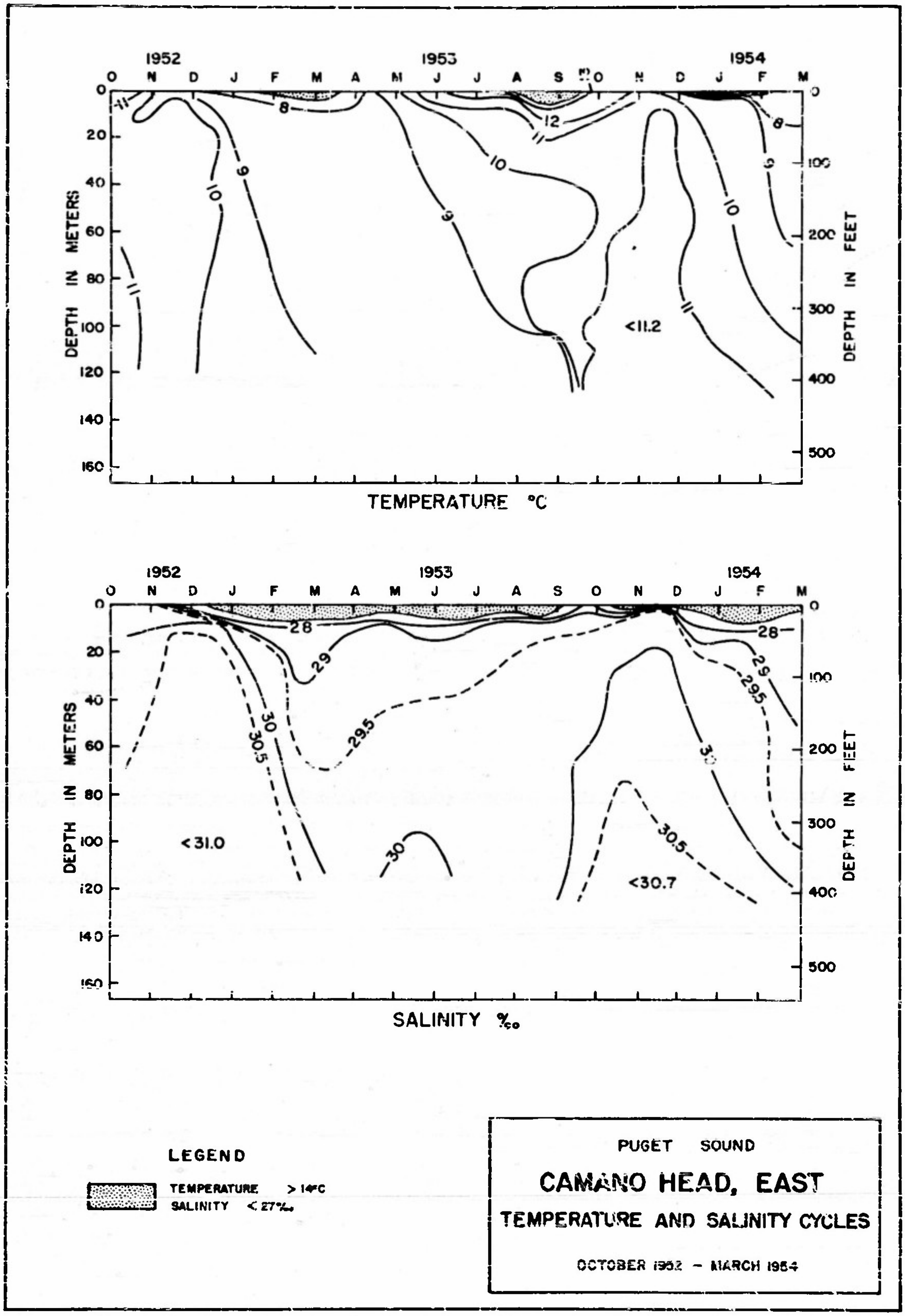

1952
1953
1954
O N D J F M A M J J A S O N D J F M
DEPTH IN METERS
DEPTH IN FEET
>8.1
>8.0
13
TEMPERATURE °C
<30.7
<30.2
SALINITY ‰
LEGEND
TEMPERATURE > 14°C.
PUGET SOUND
GORDON POINT
TEMPERATURE AND SALINITY CYCLES
OCTOBER 1952 – MARCH 1954

Fig. 10-14



1952
1953
1954
TEMPERATURE °C
SALINITY ‰
DEPTH IN METERS
DEPTH IN FEET
LEGEND
TEMPERATURE < 7°C.
SALINITY < 27 ‰
PUGET SOUND
TEKIU POINT
TEMPERATURE AND SALINITY CYCLES
OCTOBER 1952 — MARCH 1954

Fig. 10-15



1952
1953
1954
O N D J F M A M J J A S O N D J F M
DEPTH IN METERS
DEPTH IN FEET
<11.2
TEMPERATURE °C
<31.0
<30.7
SALINITY ‰
LEGEND
TEMPERATURE >14°C
SALINITY <27‰
PUGET SOUND
CAMANO HEAD, EAST
TEMPERATURE AND SALINITY CYCLES
OCTOBER 1952 – MARCH 1954

Fig. 10-16

by the M.V. BROWN BEAR or the M.V. ONCORHYNCHUS during the indicated period. Data of less continuity, but obtained over a longer period, 1932-1942, from the M.V. CATALYST support the cycles as depicted herein.

The upper water at Pillar Point (surface to 100 feet) shows a rather ill defined winter minimum, the surface water dropping to 30.9 ‰ in March 1953 and 29.2 ‰ in February 1954. This minimum follows the local precipitation and runoff cycle and can be expected to very in time and intensity from year to year. A second minimum occurred in August when the surface salinity dropped below 30.0 ‰. This minimum resulted primarily from melting snow feeding seaward from the Fraser River which peaks annually in June or July. At depths greater than 200 feet a well defined salinity maximum occurred in July or August, the period being progressively retarded as the depth increased. This summer maximum has occurred persistently in all years where sufficient data exist to define the seasonal conditions.

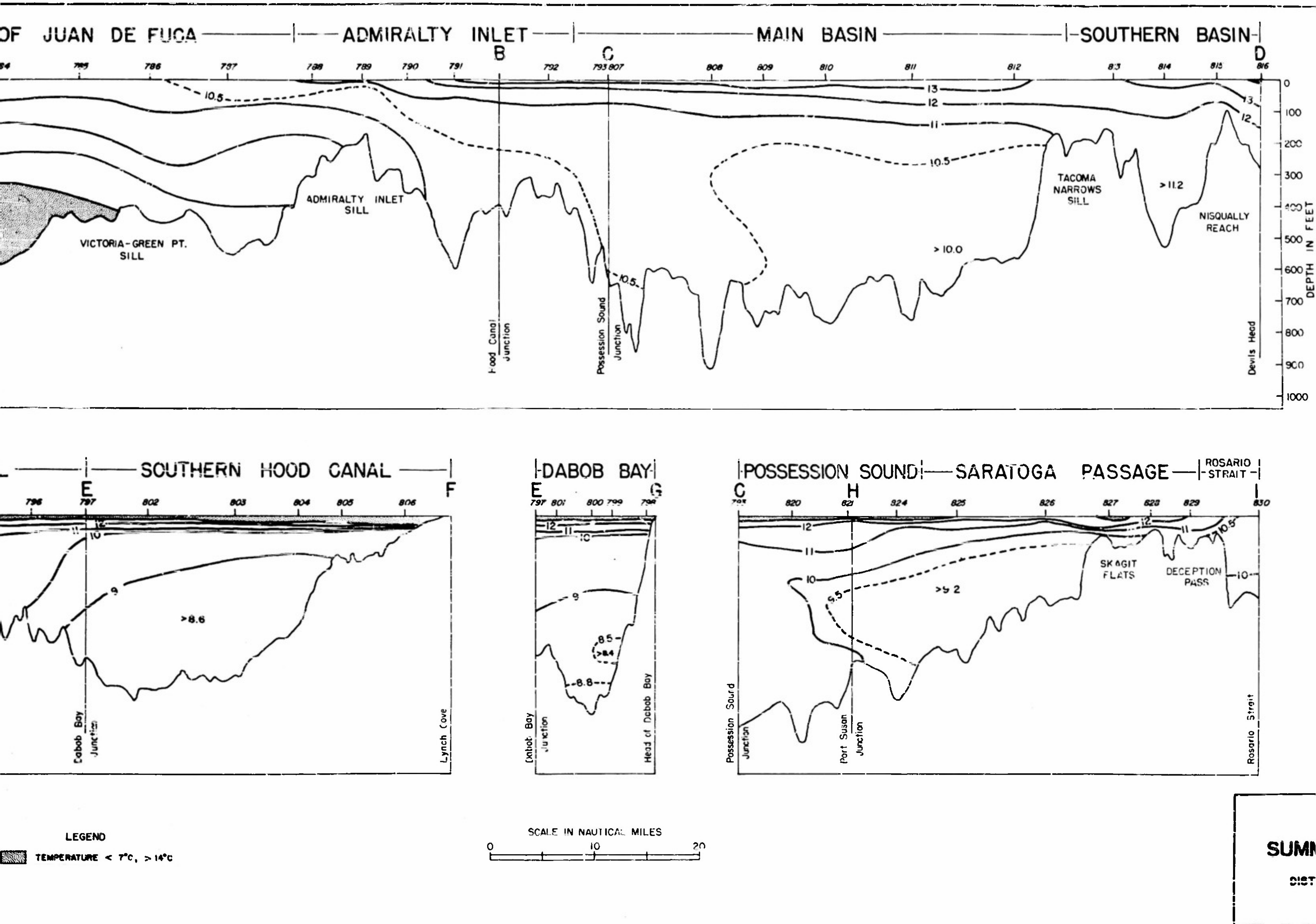
The upper waters at Point Jefferson also show the dual salinity minima, one in late winter or early spring and the other in mid-summer. The lowest average salinity for the entire water column, about 29.5 ‰, occurred in April and the highest, about 30.9 ‰ and 30.6 ‰, occurred in November of 1952 and October of 1953 respectively. The most rapid replenishment of deeper water occurs in autumn or early winter. The patterns in basins more remote from, or less well connected to, the sea as Gordon Point in southern Puget Sound, Tokiu Point in Hood Canal, and Camano Head in Port Susan, all show somewhat similar salinity patterns, but the maximum values are less, and the periods of the maxima are later in the fall or winter. The minima at depth are less well defined with little change throughout the spring and summer.

TEMPERATURE DISTRIBUTION

The following discussion of temperature in the Puget Sound system is based on measurements made simultaneously with those for salinity which were treated above. Together these two independent variables determine the density of the sea water under atmospheric pressure, commonly expressed as σ_t, which in turn greatly influences the circulation and flushing. Both variables are tied in with circulation and mixing. If allowance is made for the transfer of mass and energy across the water surface, a certain parallelism would be expected in their variations.

Summer Conditions

The summer distribution of temperature from the Strait of Juan de Fuca to the heads of the various arms is shown by mid-channel temperature profiles in Fig. 10-17. At this season the primary "cold source" is the deep water



OF JUAN DE FUCA
ADMIRALTY INLET
MAIN BASIN
SOUTHERN BASIN
B
C
D
VICTORIA-GREEN PT. SILL
ADMIRALTY INLET SILL
TACOMA NARROWS SILL
NISQUALLY REACH
> 11.2
> 10.0
10.5
13
12
11
Hood Canal Junction
Possession Sound Junction
Devils Head
DEPTH IN FEET
0
100
200
300
400
500
600
700
800
900
1000
SOUTHERN HOOD CANAL
E
F
>8.6
Dabob Bay Junction
Lynch Cove
DABOB BAY
G
8.5
>8.4
8.8
Dabob Bay Junction
Head of Dabob Bay
POSSESSION SOUND
SARATOGA PASSAGE
ROSARIO STRAIT
H
I
SKAGIT FLATS
DECEPTION PASS
9.5
10
Possession Sound Junction
Port Susan Junction
Rosario Strait
LEGEND
TEMPERATURE < 7°C, > 14°C
SCALE IN NAUTICAL MILES
0
10
20
SUMM
DIST

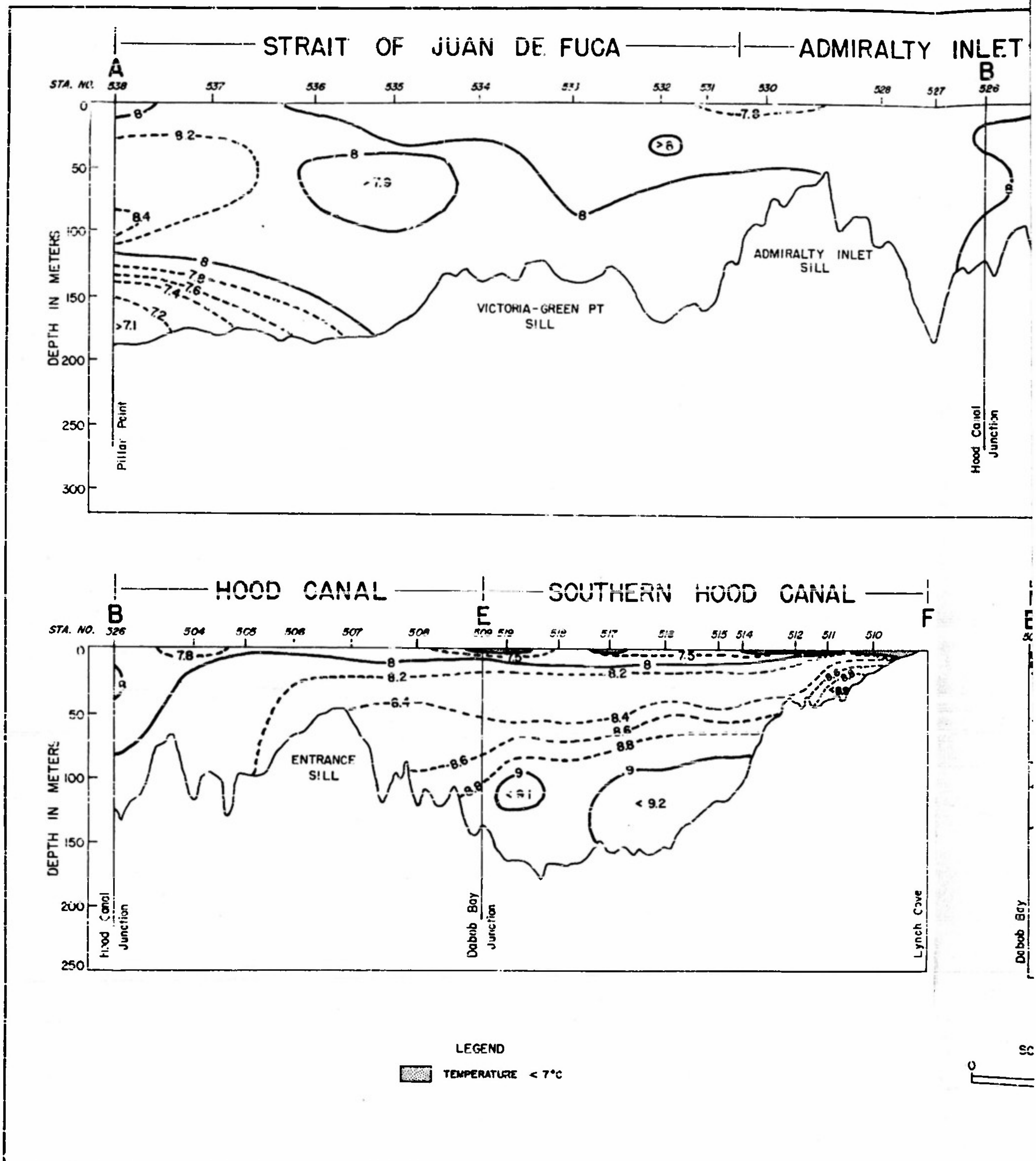
Fig. 10-

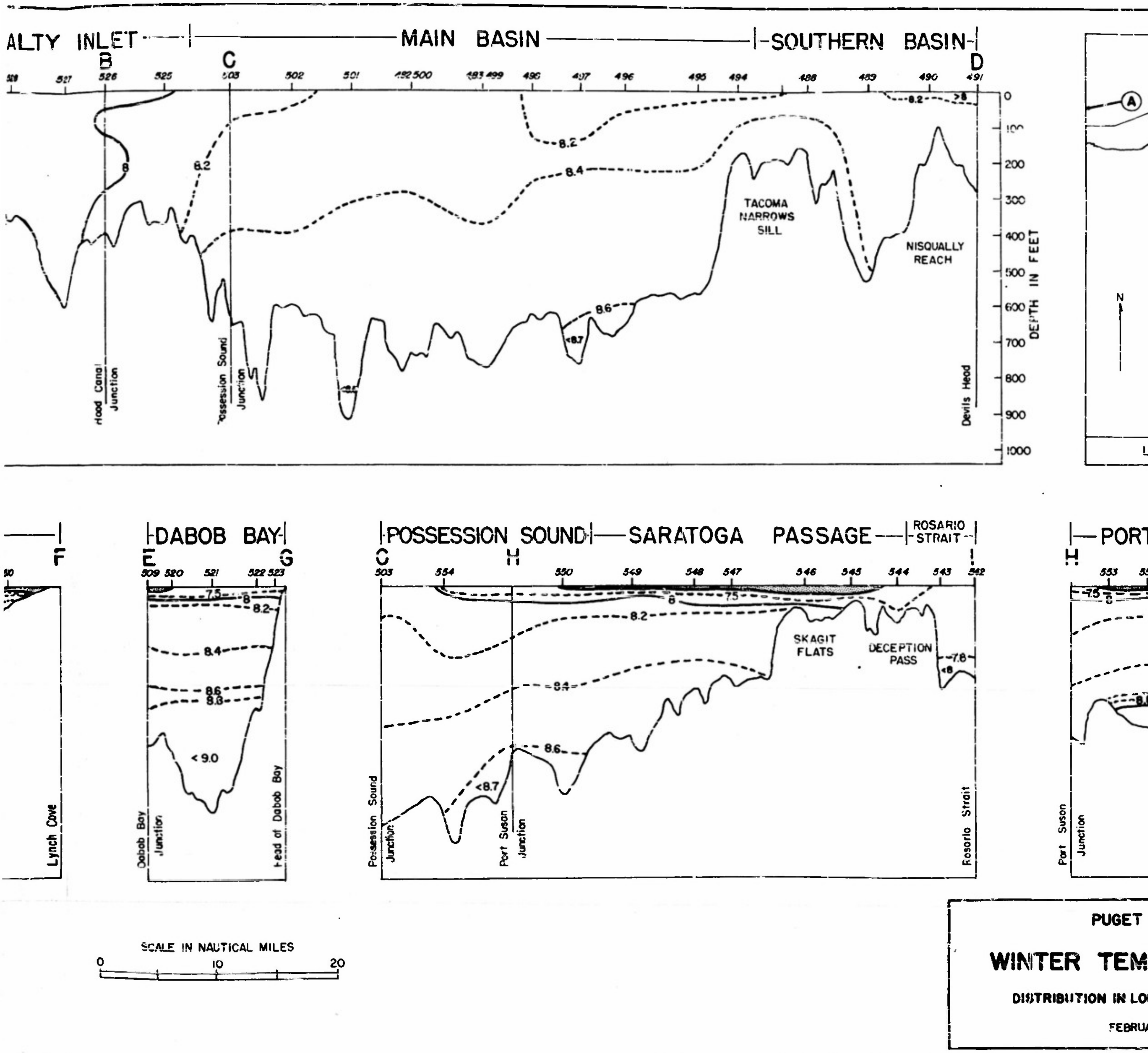
of the Strait with values less than 6.5° C. evident below 400 feet seaward of the Victoria-Green Point sill. Secondary cold sources are clouds of residual winter or spring water at depth in the inner basins, particularly that water near the heads of the basins as in Saratoga Passage, the main Puget Sound basin north of the Tacoma Narrows, southern Hood Canal, and the entrapped bottom water behind the Dabob Bay and Port Susan sills. The respective minima in these secondary sources are approximately 9.2°, 10.0°, 8.6°, 8.8°, and 8.4° C. A distinct remnant of 8.5° C. water exists at a depth slightly above sill level in the northern extremity of Dabob Bay. In the more freely circulating water not trapped behind subsidiary sills these minima and their rates of change on the warming cycle of the year afford a rough index of the relative flushing periods of the deep basin water. A higher temperature at depth generally indicates a quicker response to surface conditions. The "surface conditions" are those representative of the more or less mixed waters fed into the basins at depth from the entrance sills. The net movement at depth is directed from the entrance sills towards the heads of the basins and that near the surface in the reverse direction. Consequently the deeper water carries the "fossil" temperatures towards the head of the basin and accounts for the persistence of the temperature minima at those extremities. On the cooling cycle of the year "fossil" temperature maxima are found in the deep or mid-depth water at the basin extremities. These maxima and their change with time may be similarly used as a rough index of the flushing rate. The more rapid flushing of the southern part of the main basin of Puget Sound and that of the southern basin probably stems from the intensive mixing of large volumes of water to considerable depth in the Tacoma Narrows.

The heat source is insolation. High temperatures are most apparent in the surface water at the heads of those arms in which tidal mixing and replenishment are at a minimum. The highest temperatures 17° to 20° C. are in southern Hood Canal where the prevailing summer winds also tend to retain the locally heated water. Outside Hood Canal only occasional thin patches of surface water exceeding 15° C. are found. Surface temperatures in tributary bays and along the periphery of the main basins would, however, be somewhat higher than the mid-channel values shown. Again, as in the case of the salinity, the greatest temperature gradients within the basins are in the upper 50 feet, with relatively little change at greater depths. In Hood Canal, decreases as great as 9° C. occur in the upper 30 feet, and gradients of 0.6° C. per foot over a few feet increase in depth. In the head of the Strait of Juan de Fuca S-T-D measurements show a step wise temperature decrease accompanying the similar increase in salinity referred to previously.

Winter Conditions

The winter temperature distribution based on observations made during February 1953 on BROWN BEAR cruise no. 21 is shown in Fig. 10-18. The temperature throughout the water mass approched isothermal conditions with a


STRAIT OF JUAN DE FUCA
ADMIRALTY INLET
A
B
STA. NO.
DEPTH IN METERS
VICTORIA-GREEN PT SILL
ADMIRALTY INLET SILL
Pillar Point
Hood Canal Junction
HOOD CANAL
SOUTHERN HOOD CANAL
E
F
ENTRANCE SILL
< 9.2
Dabob Bay Junction
Lynch Cove
LEGEND
TEMPERATURE < 7°C



ALTY INLET
MAIN BASIN
SOUTHERN BASIN
B
C
D
DEPTH IN FEET
TACOMA NARROWS SILL
NISQUALLY REACH
Hood Canal Junction
Possession Sound Junction
Devils Head
8.2
8.4
8.6
<8.7
DABOB BAY
E
G
F
Lynch Cove
Dabob Bay Junction
Head of Dabob Bay
<9.0
POSSESSION SOUND
SARATOGA PASSAGE
ROSARIO STRAIT
H
SKAGIT FLATS
DECEPTION PASS
Possession Sound Junction
Port Susan Junction
Rosario Strait
PORT
Port Susan Junction
SCALE IN NAUTICAL MILES
0
10
20
PUGET
WINTER TEM
DISTRIBUTION IN LON
FEBRUA

Fig. 10-18

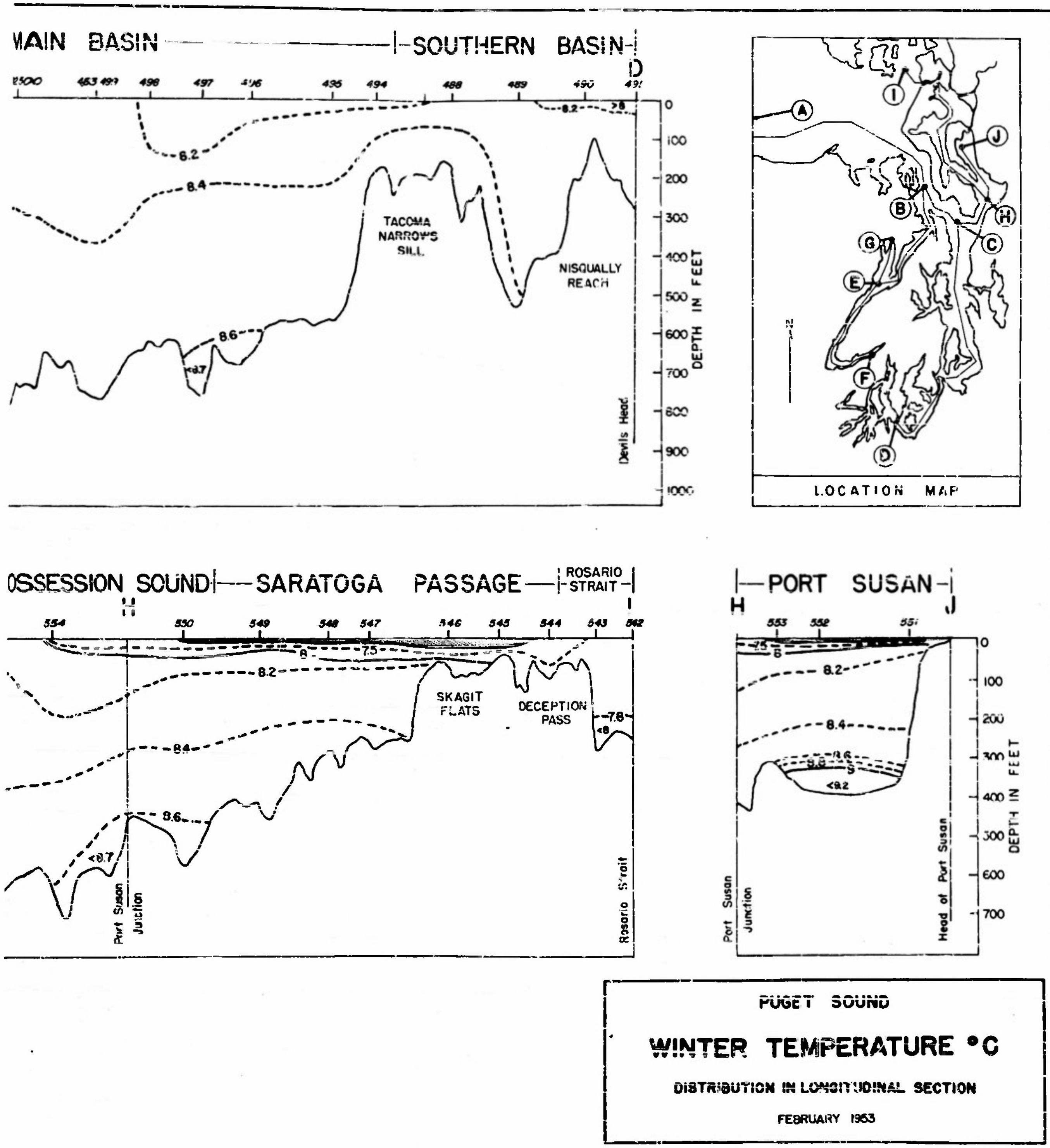

MAIN BASIN
SOUTHERN BASIN
D
TACOMA NARROWS SILL
NISQUALLY REACH
Devils Head
DEPTH IN FEET
LOCATION MAP
OSSESSION SOUND
SARATOGA PASSAGE
ROSARIO STRAIT
H
I
SKAGIT FLATS
DECEPTION PASS
Port Susan Junction
Rosario Strait
PORT SUSAN
J
Head of Port Susan
PUGET SOUND
WINTER TEMPERATURE °C
DISTRIBUTION IN LONGITUDINAL SECTION
FEBRUARY 1953

Fig. 10-18

variation of 6.0° to 9.2° C.--a range of 3.2° C. The July range was from 6.4° to 19.6° C.--a spread of 13.2° C. The colder water was at the surface and the temperature gradients were greatest in the upper layers. Below 50 feet the variation at most locations was less than 1° C. The lower maximum temperature at depth in the main basin of Puget Sound, 8.6° C., as compared to 9.2° C. in the bottom of Hood Canal, is again indicative of a more rapid flushing in the former. The temperature distribution is in agreement with a prevailing subsurface inflow and surface outflow.

General Seasonal Conditions

The seasonal changes in temperature for the period October 1952 (February 1953 at Pillar Point) to February 1954 are shown for selected locations by the following figures: Fig. 10-11, Pillar Point; Fig. 10-12, Point Jefferson; Fig. 10-14, Gordon Point; Fig. 10-15, Tekiu Point, and Fig. 10-16, Camano Head, East. The corresponding salinity distributions for their locations and time intervals have been discussed previously.

The upper water at Pillar Point (surface to a depth of 50 feet) has a maximum temperature of 11.8° C. at the surface, coinciding with the salinity minimum. This timing and temperature agrees with eight years of observations made from the M.V. CATALYST. A secondary surface maximum of 11.6° C. occurred in November. The normal temperature at that time is about 9.0° and in general the surface cools rather uniformly from the maximum in August to the winter minimum in February or March. The minimum temperature at depth, 6.3° at 600 feet, occurred as usual in August coincident with the salinity maximum. This water probably represents the deepest water from the open sea that is injected into the Strait during the year.

In August the surface water off Point Jefferson showed a temperature peak of 14.5° C. In September the same water column showed a temperature peak at depths greater than 50 feet--the maximum at 800 feet being 11.2° C. The minimum occurred in March and averaged about 8° for the entire water column--the extreme range falling within 0.3° C. The quick response of temperature at all depths in following that at the surface is indicative of the rapid flushing rate of the subsurface waters. A complete renewal of the deeper water in the southern part of the main basin probably occurs within a month. The temperature pattern at Gordon Point south of the Tacoma Narrows is similar to that at Point Jefferson, and here again a very rapid flushing rate of the primary basin is indicated. As in the case of salinity, temperatures in the basins less well connected to the sea as Hood Canal represented by Tekiu Point, and Port Susan by Camano Head, show a slower water exchange. Higher surface maxima and minima occur in response to the seasons, but the changes in values at depth lag considerably behind those at the surface, particularly during the spring and summer.

DENSITY DISTRIBUTION

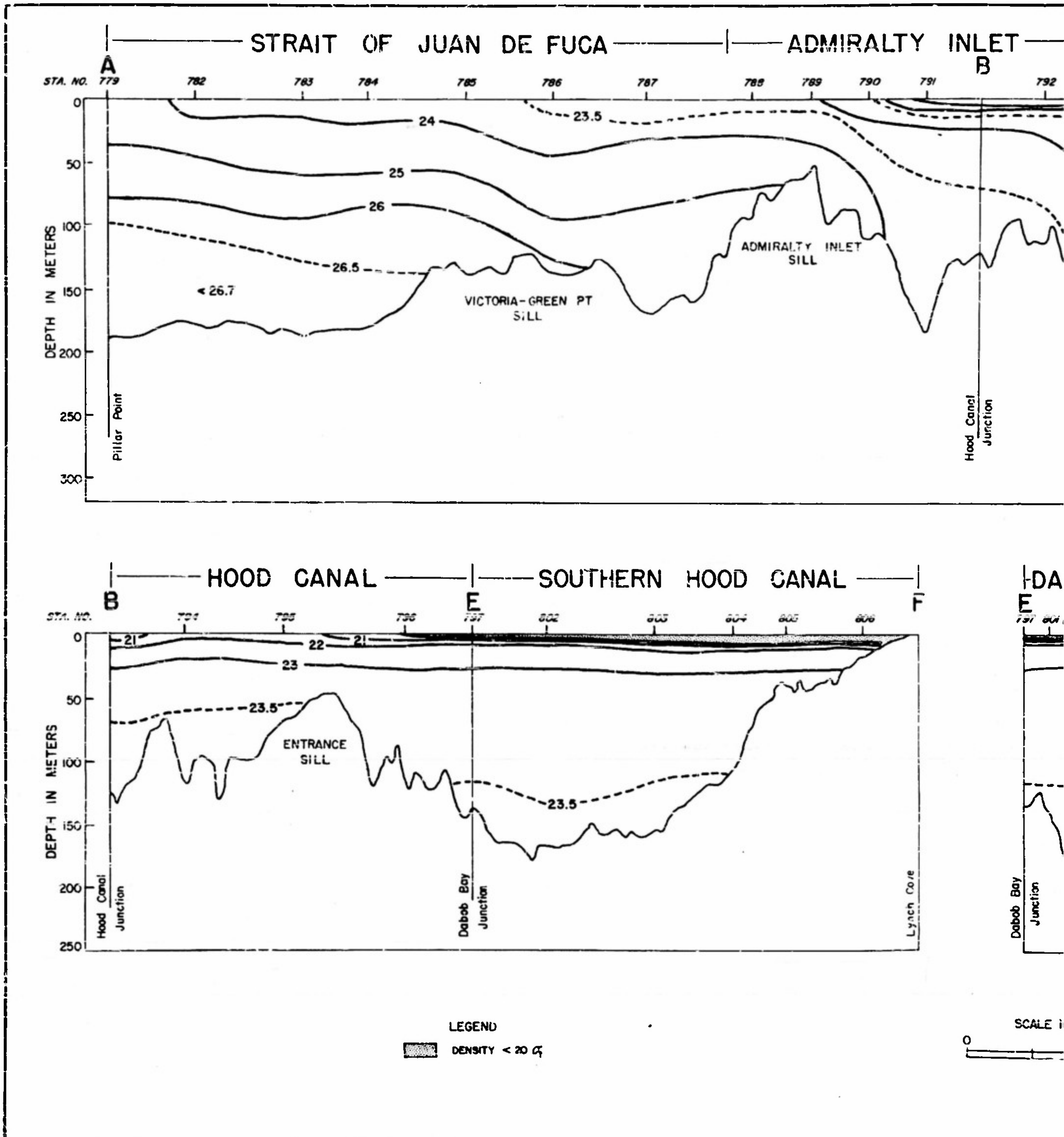
The density distributions for summer and winter conditions in the Puget Sound system are shown in Figs. 10-19 and 10-20 respectively. The density is expressed as sigma-t (σ_t) which is defined by the equation

$$\sigma_t = (\rho s,t,o-1) \quad (1000)$$

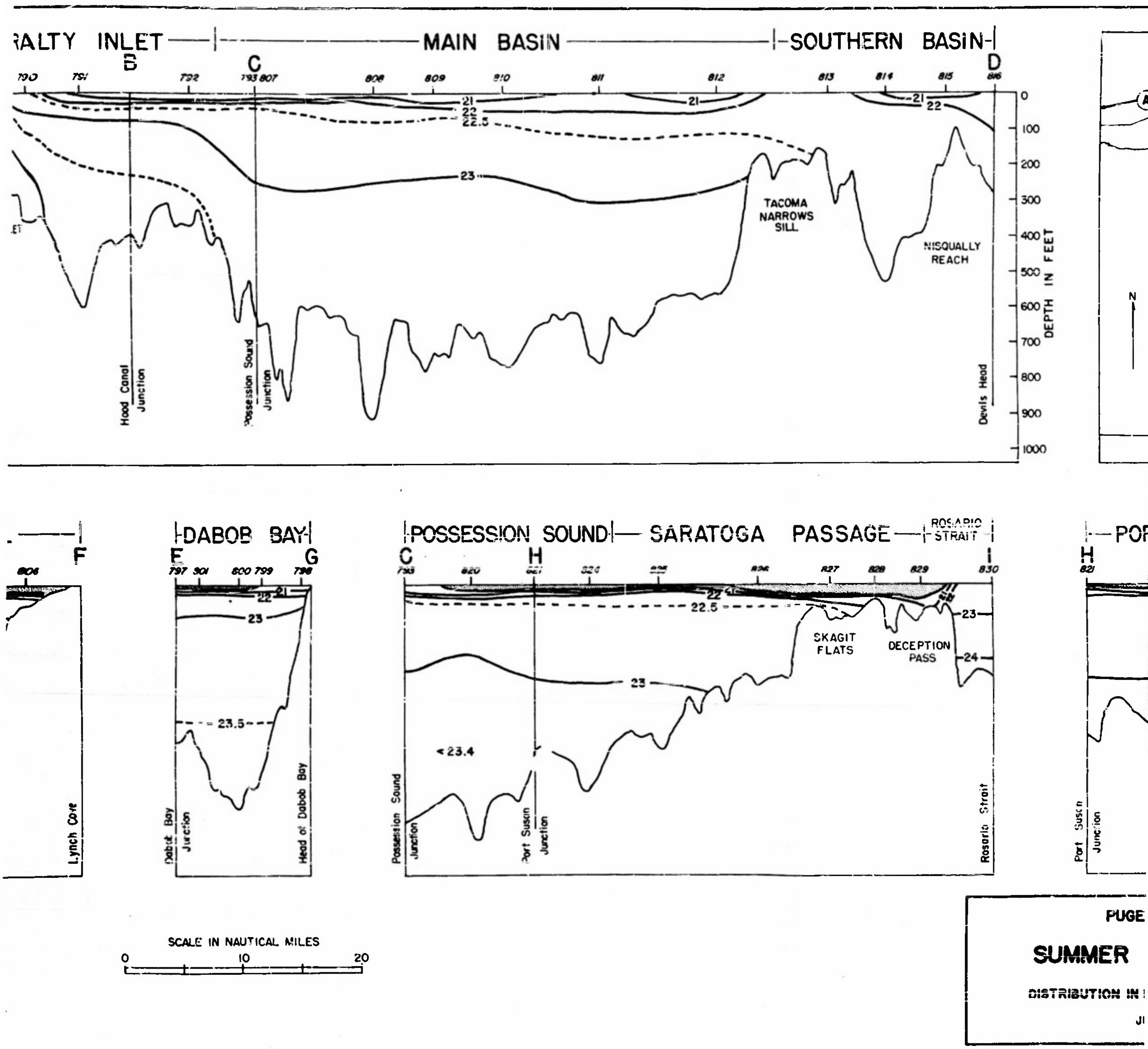
where $\rho_{s,t,o}$ is the actual density of the water at the given salinity (s), temperature (t), and atmospheric or zero sea pressure (o). The distribution of salinity and temperature on which these density profiles are based has been portrayed in Figs. 10-9, 10-10, 10-17, and 10-18, discussed above. The density increases with increasing salinity and, over the range of conditions normally encountered in Puget Sound, with decreasing temperature. In summer with increasing depth the temperature decreases and the salinity increases --both factors tending to increase the density and make the water column stable. In winter, during periods of cold weather, surface cooling tends to increase the density causing convective sinking in isohaline water and tending to reduce the stability of water stratified by the salinity distribution. The along-channel slopes of the equal density or isopycnic lines in narrow passages is indicative of the tendency of the deeper water to move in--finding its own density level. This motion would result in the absence of other forces, and with some reservations can be taken as a guide to the probable circulation in Puget Sound.

Summer Conditions

The summer density distribution (Fig. 10-19) shows a well stratified surface layer, particularly in Hood Canal, and from Possession Sound to the heads of the northern arms, closely paralleling the salinity structure. Laterally, in going seaward from the heads of the various arms, the densities increase and show rather abrupt jumps in crossing the principal sills. The slopes of the density lines indicate a net inflow at depth and outflow at the surface. The isolines were not selected with close enough increments to show detail of the microstructure at depth. This microstructure is particularly important at the level of the deeper sills leading to Dabob Bay and Port Susan. In both instances all variables examined indicate that flushing of these arms was occurring above sill level and not below. Although the density stratification was slight, it was sufficient to prevent vertical mixing from the limited motion at sill depth. Flushing in these cases must depend almost entirely on bodily displacement by more dense water, intruding after it has filled the main basins to sill level. This displacement flushing occurred in September in Port Susan and was very rapid throughout most of the Sound during that period. The critical density had not been reached in Dabob Bay by mid-winter 1953-1954 although partial flushing did occur in November. A partial flushing of Hood Canal by less dense water appears to have occurred through turbulent mixing accompanying the inflowing jet of this lighter water from the



STRAIT OF JUAN DE FUCA
ADMIRALTY INLET
A
B
STA. NO.
779
782
783
784
785
786
787
788
789
790
791
792
DEPTH IN METERS
24
23.5
25
26
26.5
< 26.7
ADMIRALTY INLET SILL
VICTORIA-GREEN PT SILL
Pillar Point
Hood Canal Junction
HOOD CANAL
SOUTHERN HOOD CANAL
E
F
21
22
23
23.5
ENTRANCE SILL
Hood Canal Junction
Dabob Bay Junction
Lynch Cove
LEGEND
DENSITY < 20 σ_t
SCALE



RALTY INLET
MAIN BASIN
SOUTHERN BASIN
B
C
D
791
792
793 807
808
809
810
811
812
813
814
815
816
21
22
22.5
23
TACOMA NARROWS SILL
NISQUALLY REACH
0
100
200
300
400
500
600
700
800
900
1000
DEPTH IN FEET
Hood Canal Junction
Possession Sound Junction
Devils Head
N
A
F
806
Lynch Cove
DABOB BAY
E
G
797
801
800
799
798
23.5
Dabob Bay Junction
Head of Dabob Bay
POSSESSION SOUND
SARATOGA PASSAGE
ROSARIO STRAIT
H
I
820
821
826
827
828
829
830
24
SKAGIT FLATS
DECEPTION PASS
< 23.4
Possession Sound Junction
Port Susan Junction
Rosario Strait
POR
821
SCALE IN NAUTICAL MILES
0
10
20
PUGE
SUMMER
DISTRIBUTION IN

Fig. 10-19

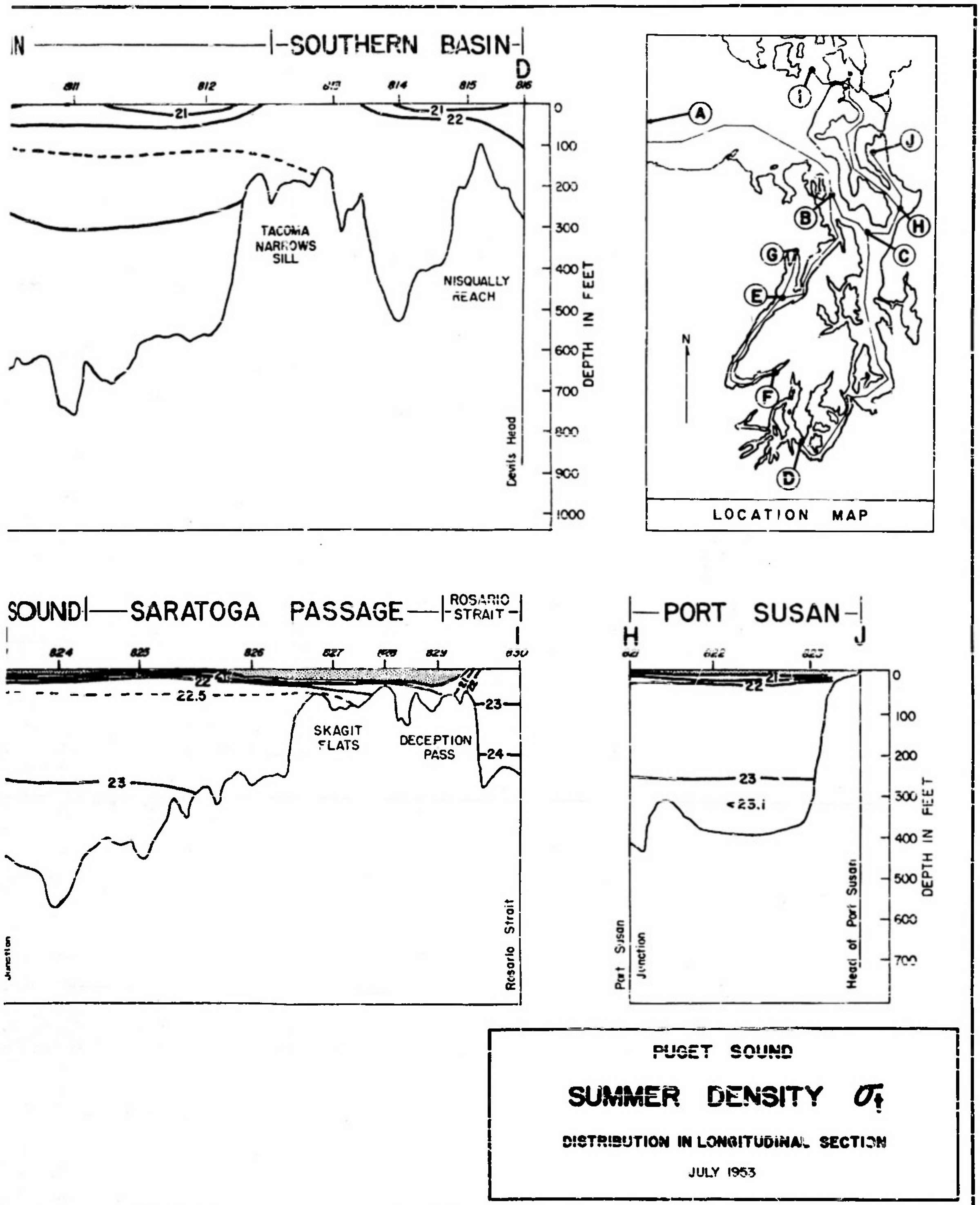
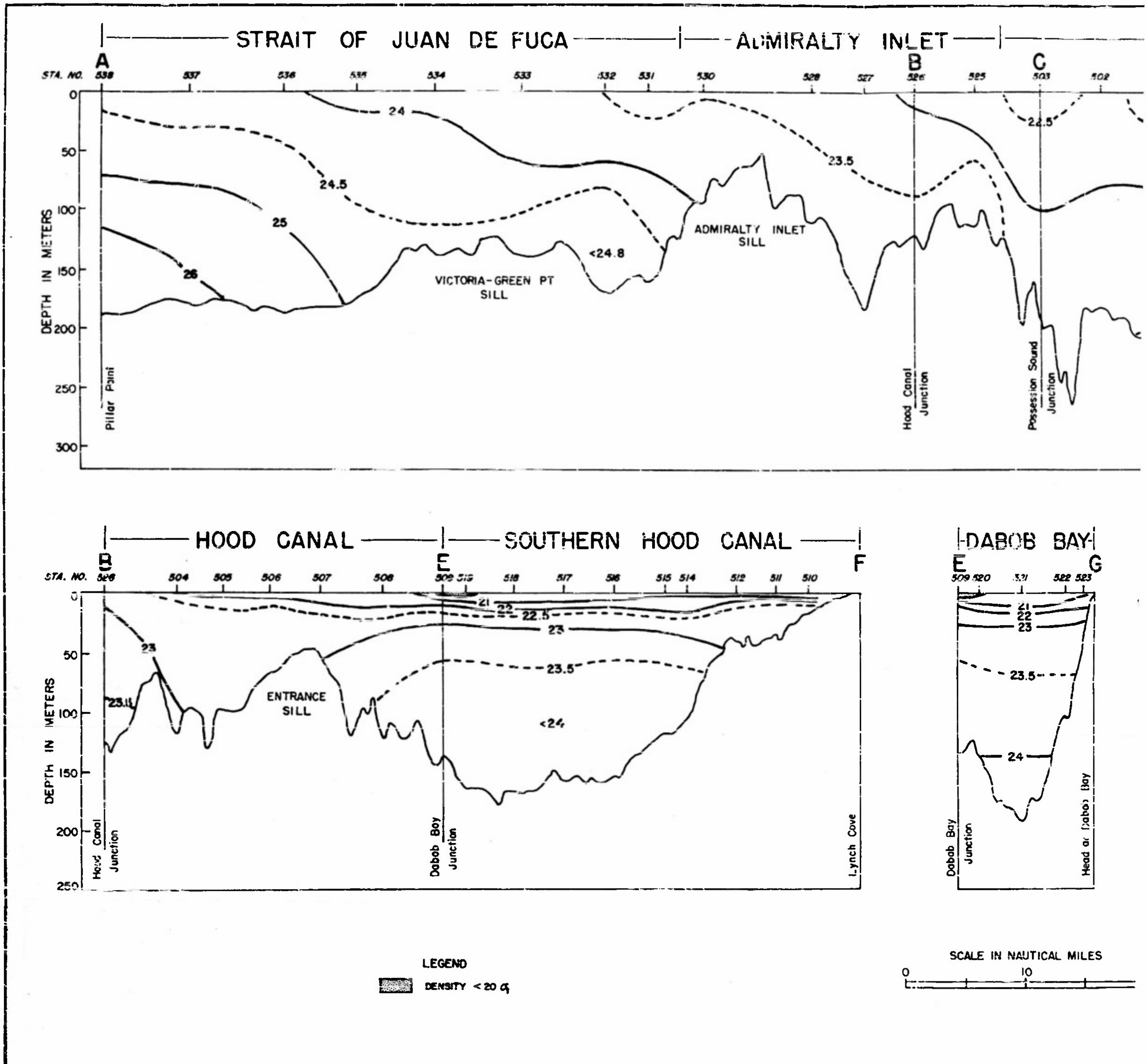
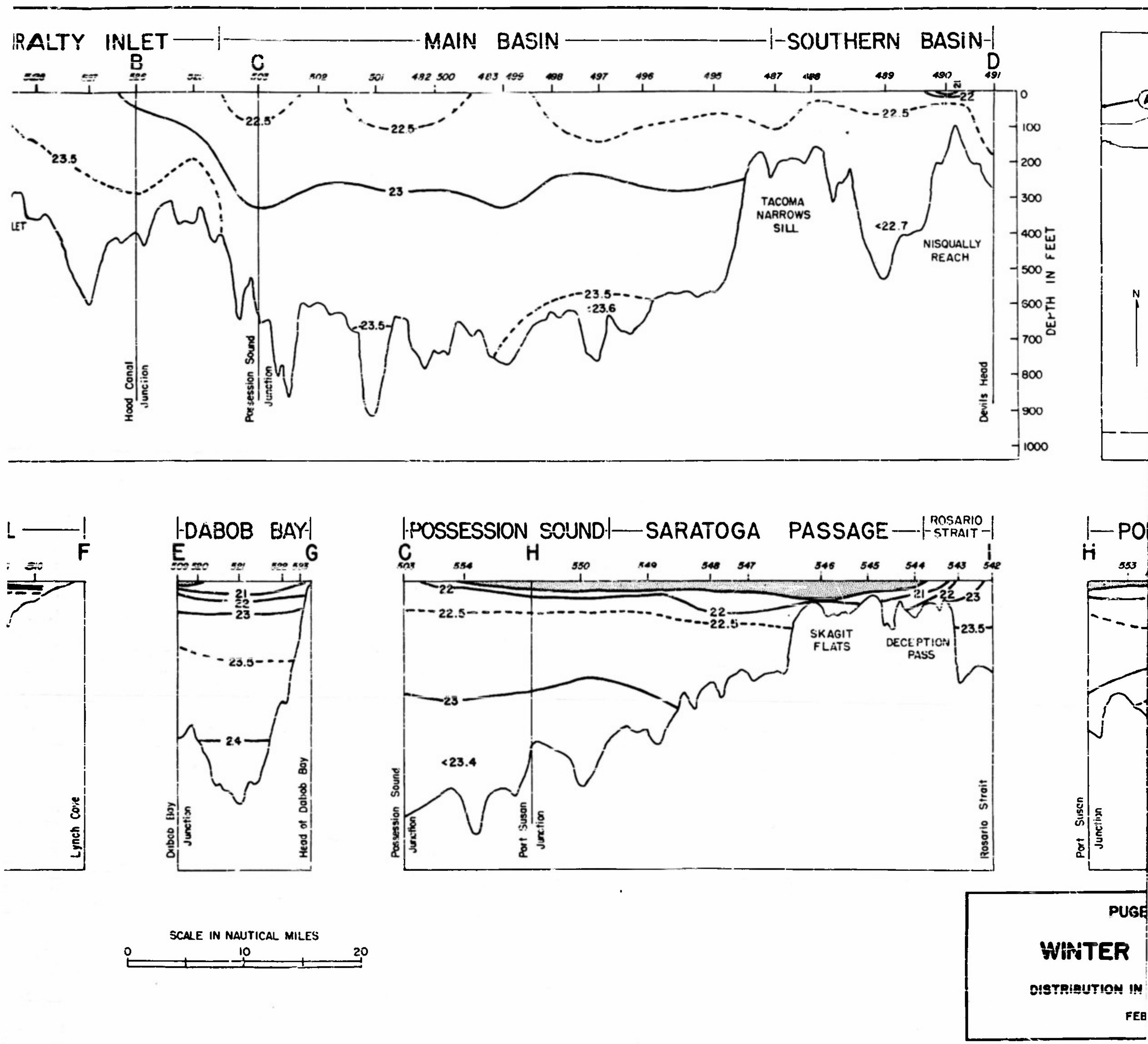

SOUTHERN BASIN
D
811
812
814
815
816
21
22
TACOMA NARROWS SILL
NISQUALLY REACH
DEPTH IN FEET
Devils Head
0
100
200
300
400
500
600
700
800
900
1000
LOCATION MAP
N
A
B
C
D
E
F
G
H
I
J
SOUND
SARATOGA PASSAGE
ROSARIO STRAIT
I
824
825
826
827
829
830
22.5
23
24
SKAGIT FLATS
DECEPTION PASS
Rosario Strait
PORT SUSAN
H
J
822
823
21
22
23
< 23.1
Port Susan Junction
Head of Port Susan
PUGET SOUND
SUMMER DENSITY σt
DISTRIBUTION IN LONGITUDINAL SECTION
JULY 1953

Fig. 10-19

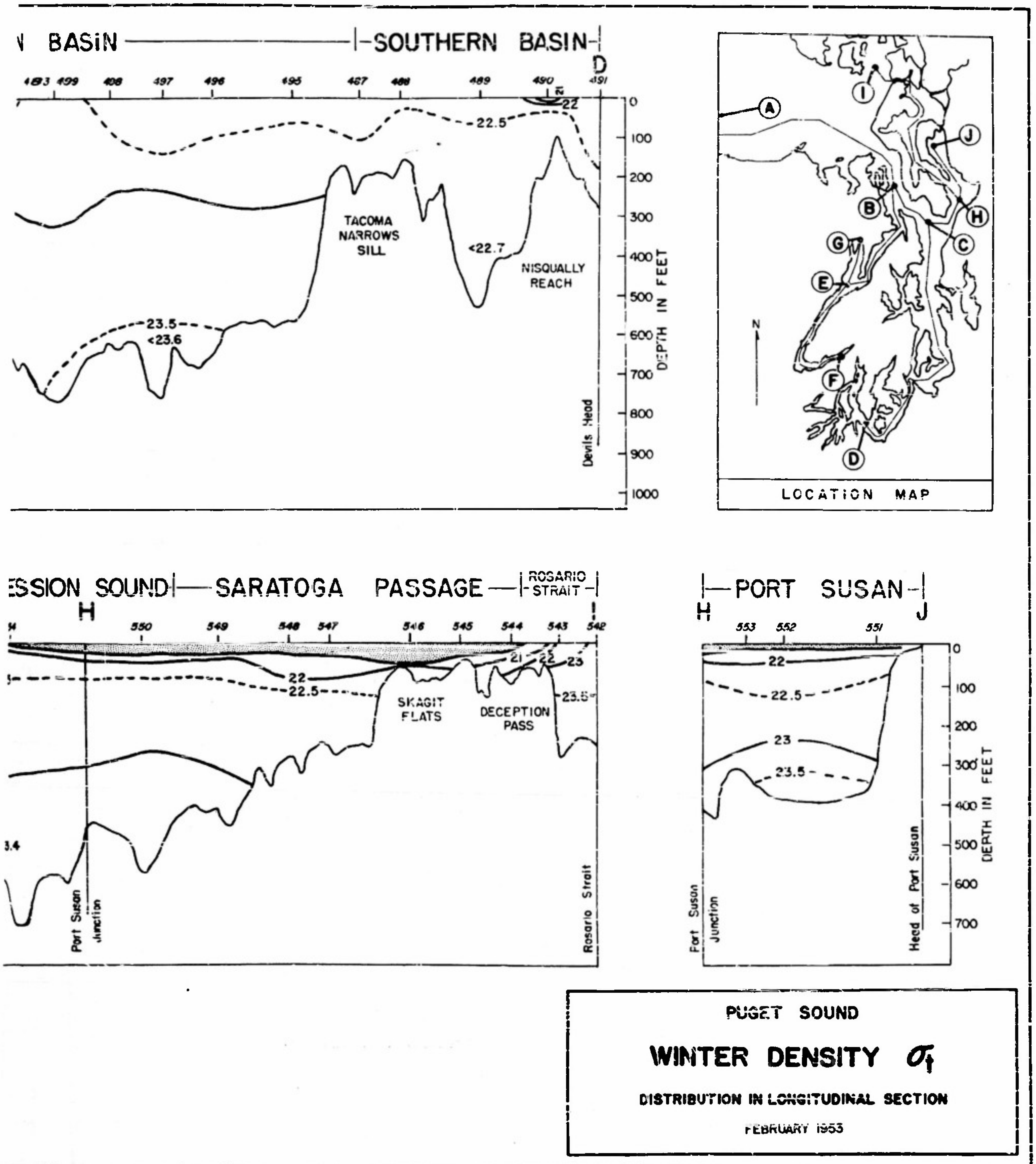


STRAIT OF JUAN DE FUCA
ADMIRALTY INLET
STA. NO.
DEPTH IN METERS
VICTORIA-GREEN PT SILL
ADMIRALTY INLET SILL
Pillar Point
Hood Canal Junction
Possession Sound Junction
HOOD CANAL
SOUTHERN HOOD CANAL
DABOB BAY
ENTRANCE SILL
Dabob Bay Junction
Lynch Cove
Head of Dabob Bay
LEGEND
DENSITY < 20 σ_t
SCALE IN NAUTICAL MILES



RALTY INLET
MAIN BASIN
SOUTHERN BASIN
B
C
D
TACOMA NARROWS SILL
NISQUALLY REACH
DEPTH IN FEET
Hood Canal Junction
Possession Sound Junction
Devils Head
DABOB BAY
POSSESSION SOUND
SARATOGA PASSAGE
ROSARIO STRAIT
E
F
G
H
I
SKAGIT FLATS
DECEPTION PASS
Lynch Cove
Dabob Bay Junction
Head of Dabob Bay
Port Susan Junction
Rosario Strait
SCALE IN NAUTICAL MILES
PUGE
WINTER
DISTRIBUTION IN
FEB

Fig. 10-20



BASIN
SOUTHERN BASIN
D
TACOMA NARROWS SILL
NISQUALLY REACH
Devils Head
DEPTH IN FEET
LOCATION MAP
N
SESSION SOUND
SARATOGA PASSAGE
ROSARIO STRAIT
H
SKAGIT FLATS
DECEPTION PASS
Port Susan Junction
Rosario Strait
PORT SUSAN
H
J
Head of Port Susan
PUGET SOUND
WINTER DENSITY σ_t
DISTRIBUTION IN LONGITUDINAL SECTION
FEBRUARY 1953

Fig. 10-20

entrance sill. The bottom topography favors this type of flushing in Hood Canal proper but not in Dabob Bay. In most natural situations flushing by less dense water due to momentum head can be expected to be very slow compared to the displacement type. Theoretically the incoming water will interleaf with the basin water at its appropriate density level, and promote flushing at this level and lesser depths. Flushing can thus theoretically occur at almost any depth. In the Sound system, however, the inflow appears to occur most frequently at the bottom.

Winter Conditions

The winter density structure shown in Fig. 10-20 is closely similar to that in summer, but the density values are higher within the basins and the vertical stability less as a consequence of the surface cooling. In the Strait of Juan de Fuca the densities are less than in summer owing to the lower salinities. As a consequence the lateral gradients across the sills are less in winter than in summer.

TEMPERATURE-SALINITY RELATIONSHIPS

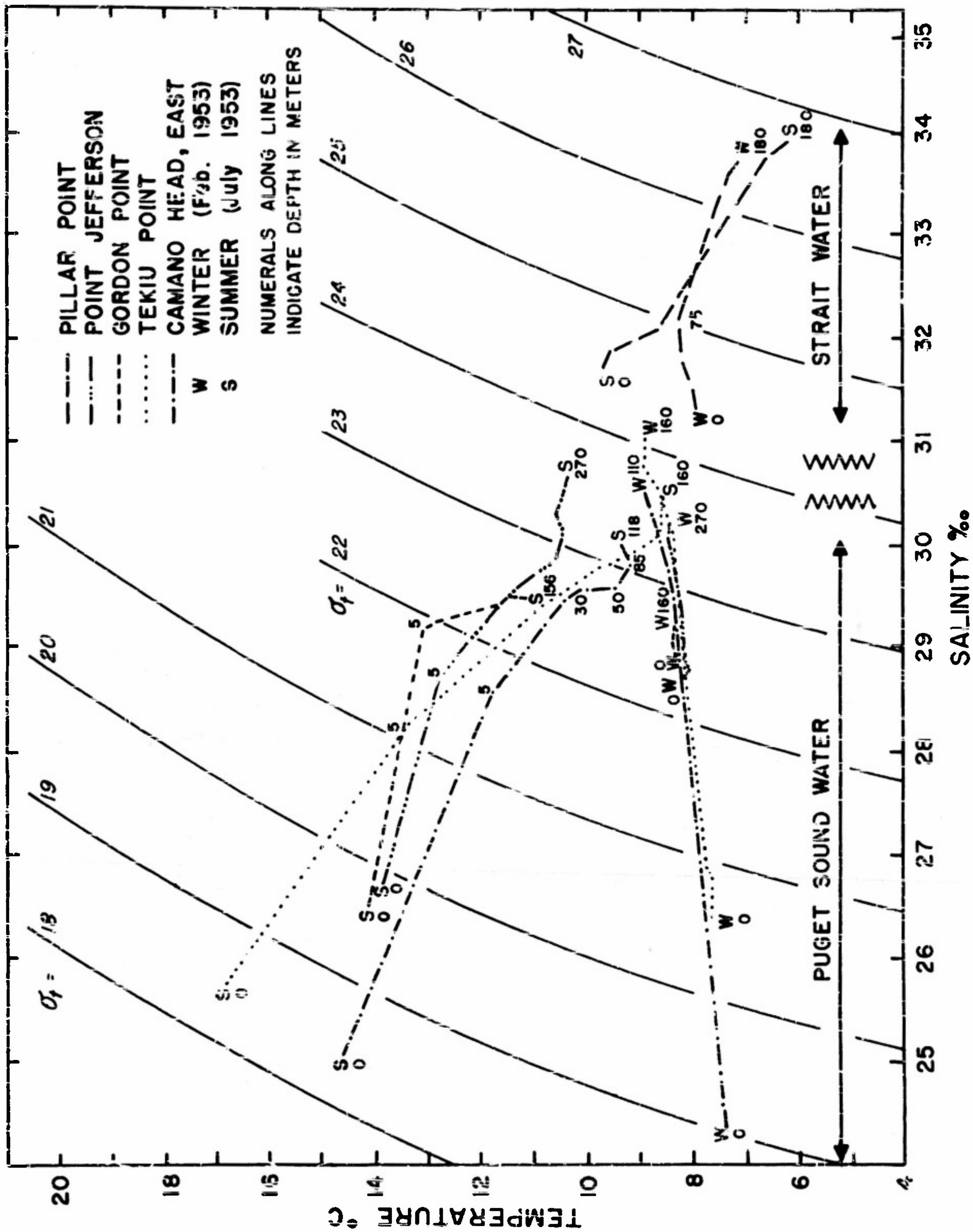
Besides the temperature, salinity, and density of themselves, the temperature-salinity relationships are useful in identifying and tracking the water within the Puget Sound system. Figure 10-21 shows the temperature-salinity curves for five stations at which the annual temperature and salinity cycles have been shown above. A distinct change in water characteristics occurs from summer to winter in the Strait. Some continuity between the surface water in the Strait and the deeper water in the inner basins is apparent. The divergence between summer and winter conditions within the basins is considerable. The seasonal variation in the position of the T-S lines, if consistent, may afford a time base useful in identifying the waters and studying their circulation and mixing.

DISSOLVED OXYGEN

The following discussion is based on measurements taken simultaneously with those for salinity and temperature which were previously discussed. The distribution of oxygen is affected by the circulation and mixing of the water within the Puget Sound Basin as well as by exchange across the sea surface and biochemical processes. Oxygen values are expressed in milligram-atoms per liter. To find milliliters per liter multiply the results by 11.2.

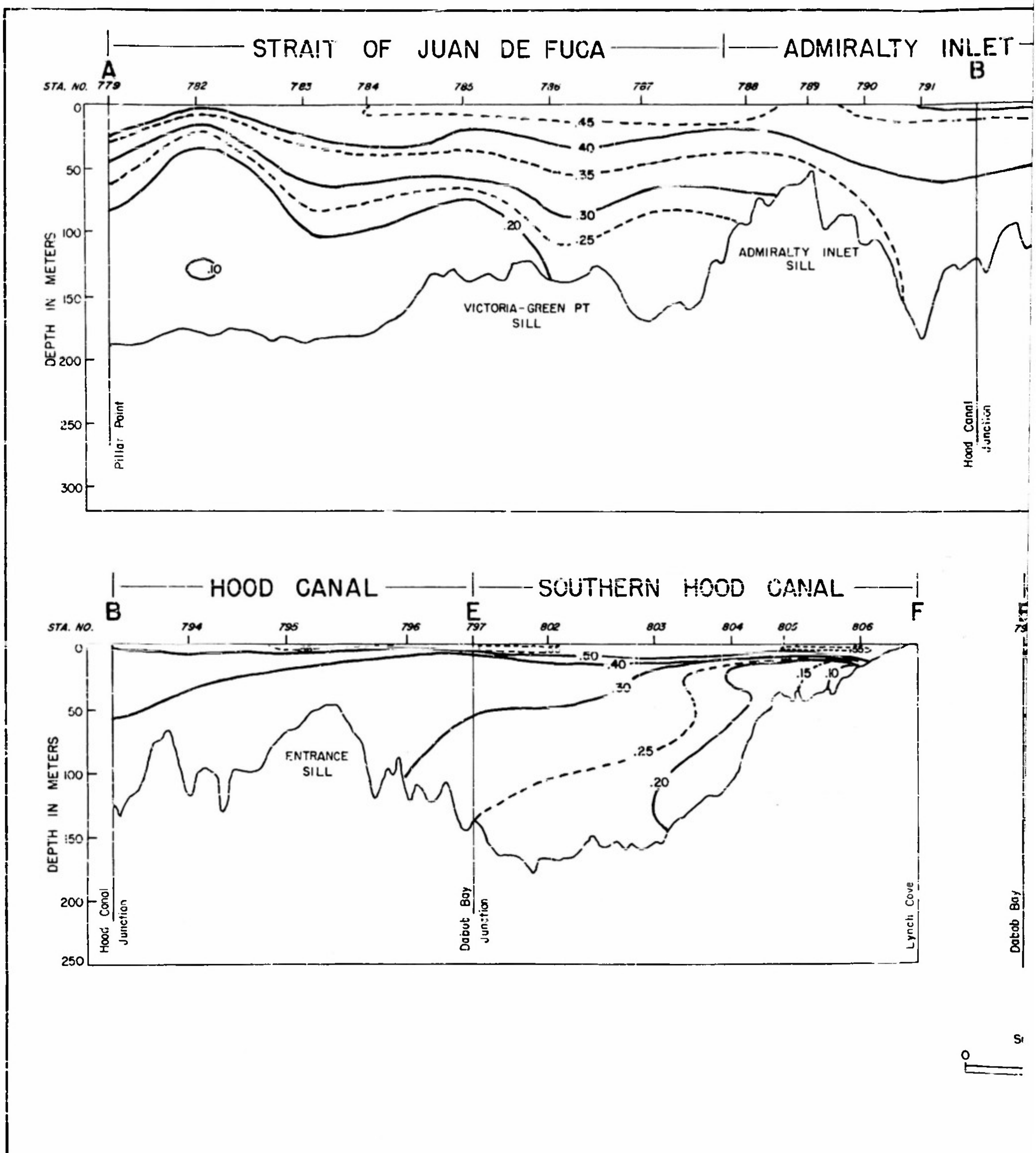
Summer Conditions

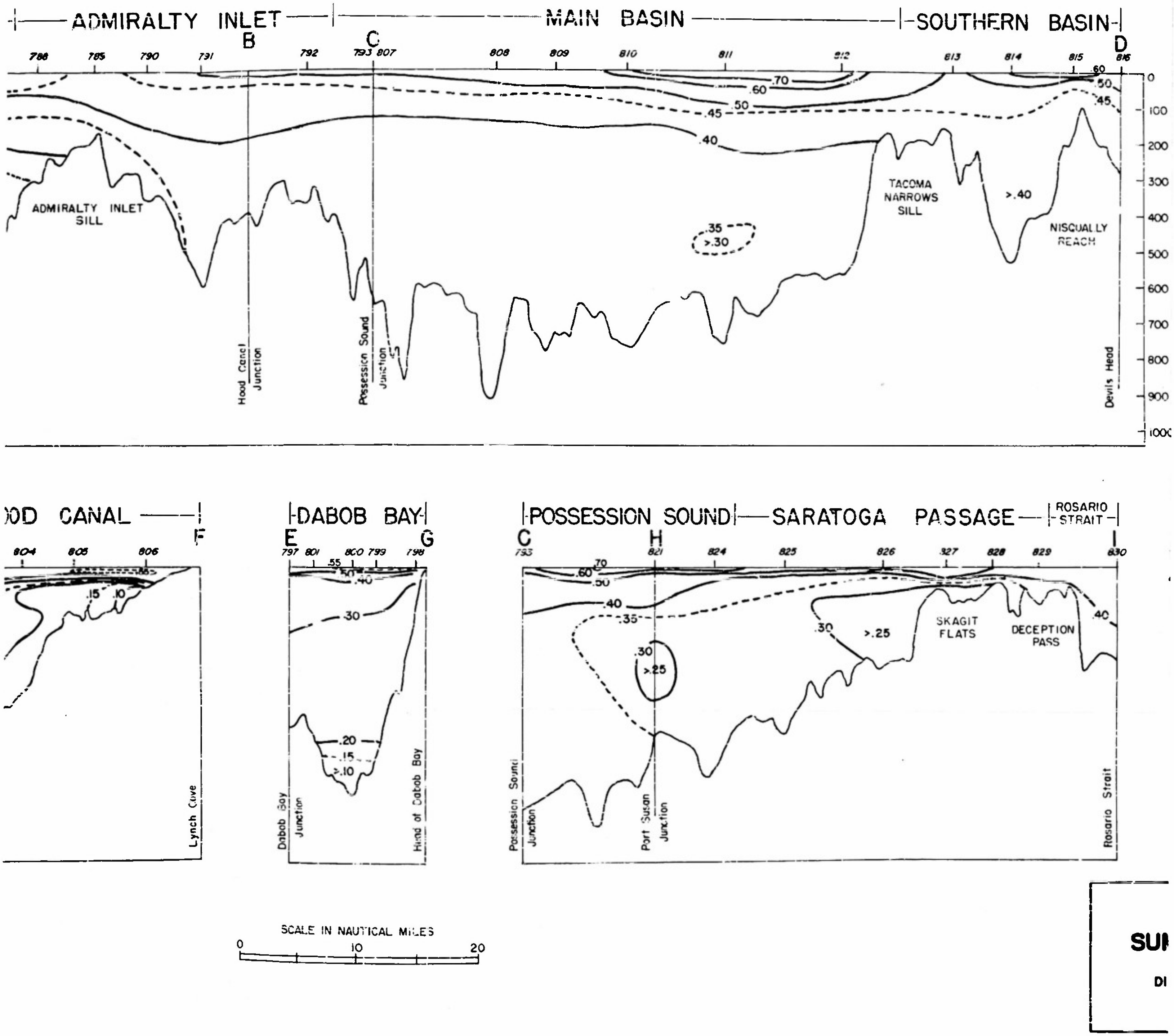
The summer dissolved oxygen distribution is shown in Fig. 10-22. The water entering the Strait of Juan de Fuca is low in oxygen (0.1-0.2 milligram -atoms per liter) supporting other evidence that at this season coastal



Temperature-salinity curves for summer and winter for five stations.

Fig. 10-21


STRAIT OF JUAN DE FUCA
ADMIRALTY INLET
A
B
STA. NO. 779 782 783 784 785 786 787 788 789 790 791
.45
.40
.35
.30
.25
.20
.10
ADMIRALTY INLET SILL
VICTORIA-GREEN PT SILL
DEPTH IN METERS
0 50 100 150 200 250 300
Pillar Point
Hood Canal Junction
HOOD CANAL
SOUTHERN HOOD CANAL
B
E
F
STA. NO. 794 795 796 797 802 803 804 805 806
.50
.40
.30
.25
.20
.15
.10
ENTRANCE SILL
DEPTH IN METERS
0 50 100 150 200 250
Hood Canal Junction
Dabob Bay Junction
Lynch Cove


ADMIRALTY INLET
MAIN BASIN
SOUTHERN BASIN
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D
788
785
790
791
792
793 807
808
809
810
811
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814
815
816
.70
.60
.50
.45
.40
.35
>.30
>.40
ADMIRALTY INLET SILL
TACOMA NARROWS SILL
NISQUALLY REACH
Hood Canal Junction
Possession Sound Junction
Devils Head
0
100
200
300
400
500
600
700
800
900
1000
OOD CANAL
F
804
805
806
.15
.10
Lynch Cove
DABOB BAY
E
G
797
801
800
799
798
.55
.50
.40
.30
.20
.15
>.10
Dabob Bay Junction
Head of Dabob Bay
POSSESSION SOUND
SARATOGA PASSAGE
ROSARIO STRAIT
C
H
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793
821
824
825
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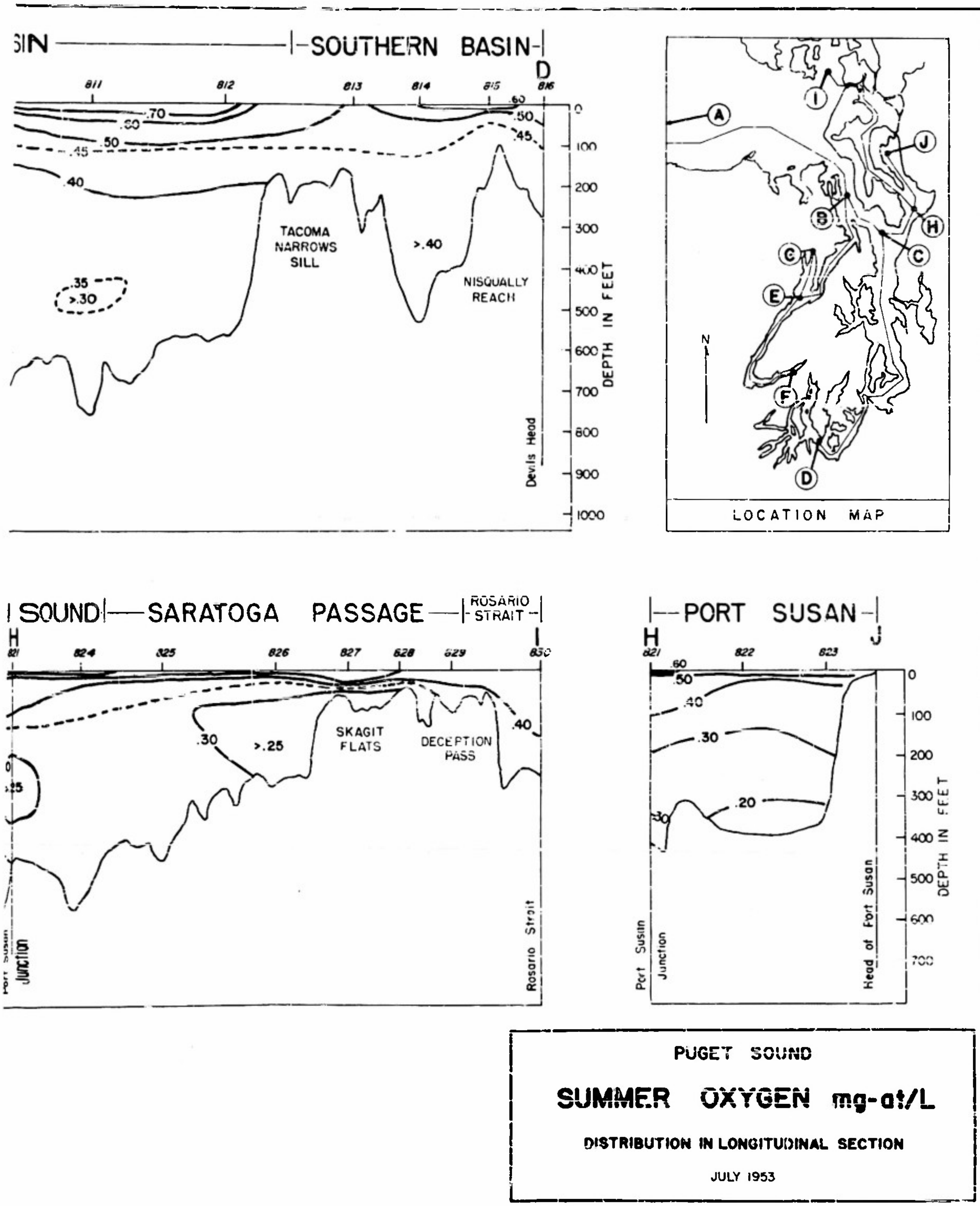
827
828
829
830
.70
.60
.50
.40
.35
.30
>.25
SKAGIT FLATS
DECEPTION PASS
Possession Sound Junction
Port Susan Junction
Rosario Strait
SCALE IN NAUTICAL MILES
0
10
20
SU
DI

Fig. 10



PUGET SOUND

SUMMER OXYGEN mg-at/L

DISTRIBUTION IN LONGITUDINAL SECTION

JULY 1953

Fig. 10-22

oceanic water travels upward from a greater depth in entering the Strait of Juan de Fuca. This water is the same as that discussed in the salinity distribution. Most of the low oxygen content water is stopped, or intermixed with that of higher oxygen content, at the Victoria-Green Point and Admiralty Inlet sills before reaching Puget Sound proper.

The higher values in Puget Sound proper (0.3-0.7 milligram-atoms per liter) are due to surface exchange and to photosynthesis which occurs in the upper layers. High oxygen concentrations near the surface are evident in the less mixed portions of the region. The highest values usually occur in late spring (April and May) accompanying heavy blooms of phytoplankton.

Locally at depths greater than 30 to 60 feet below the surface the processes of respiration and decay use up oxygen more rapidly than it is supplied by photosynthesis and aeration. As a result, the concentration of dissolved oxygen in a particular water mass decreases as long as it remains below this surface layer. The change in oxygen concentration with time thus in some instances affords a tool for dating the water mass. An increase in oxygen at depth must depend on advection and/or mixing.

Several prominent regions low in oxygen occur of which one is in southern Hood Canal. The low concentration here, dropping below 0.05 milligram-atoms per liter during summer, is attributed to the oxidation of the large amount of organic material formed locally. This material has settled on or near the bottom. Circulation and mixing are limited in this extremity of the basin. Some of the water does mix laterally however and spread along isopycnic lines in a prominent tongue extending seaward from Lynch Cove at a depth of about 100 feet. This tongue becomes more pronounced in the fall and disappears in winter. A secondary lobe of low oxygen water extends along the bottom to a depth exceeding 400 feet. In this lobe particulate matter appears to be settling out contrary to the prevailing upward water movement.

A second prominent low oxygen zone is found in Dabob Bay. The water below sill depth (450 feet) is restricted from actively circulating and consequently the dissolved oxygen content decreases with time due to biochemical reactions. The entrapped water showed only partial flushing in mid-winter of 1953-1954, and the gradually diminishing oxygen concentration and constant mass properties indicated that it had been there for at least nine months.

Another oxygen sink similar to Dabob Bay is evident in Port Susan. The water behind this sill was trapped for most of the summer of 1953 but was replaced during the active circulation that occurred during the fall. The oxygen values do not become as low as in Dabob Bay at corresponding times. Water of low oxygen content has intruded into Possession Sound from Port Susan by flowing along isopycnic lines, and is shown as an isolated pocket in that area.

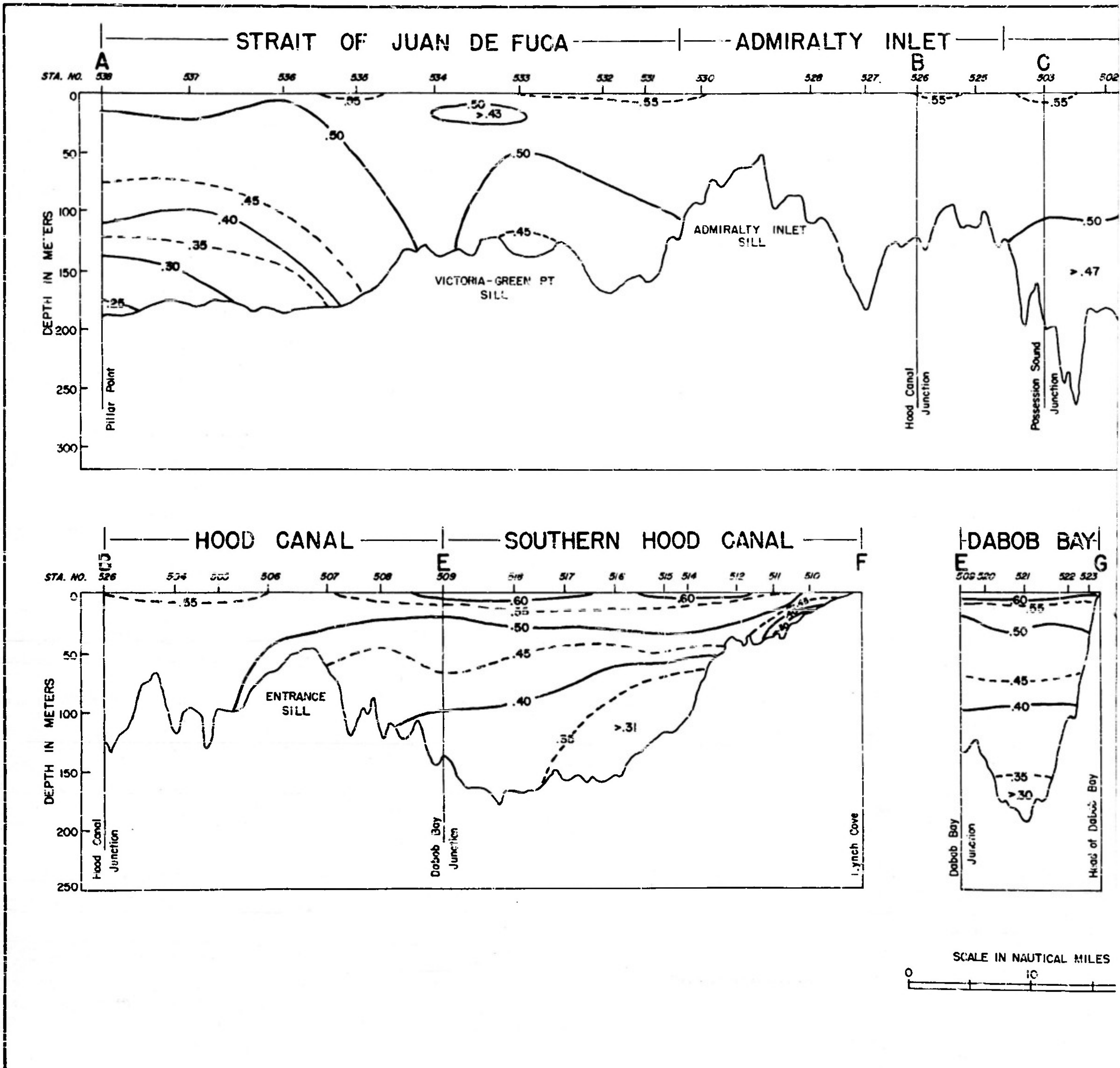
Low oxygen concentrations are also found in the head of Saratoga Passage near Skagit Flats and in the head of Carr Inlet (not shown). These are in line with the general movement of the deeper water towards the heads of the arms.

Winter Conditions

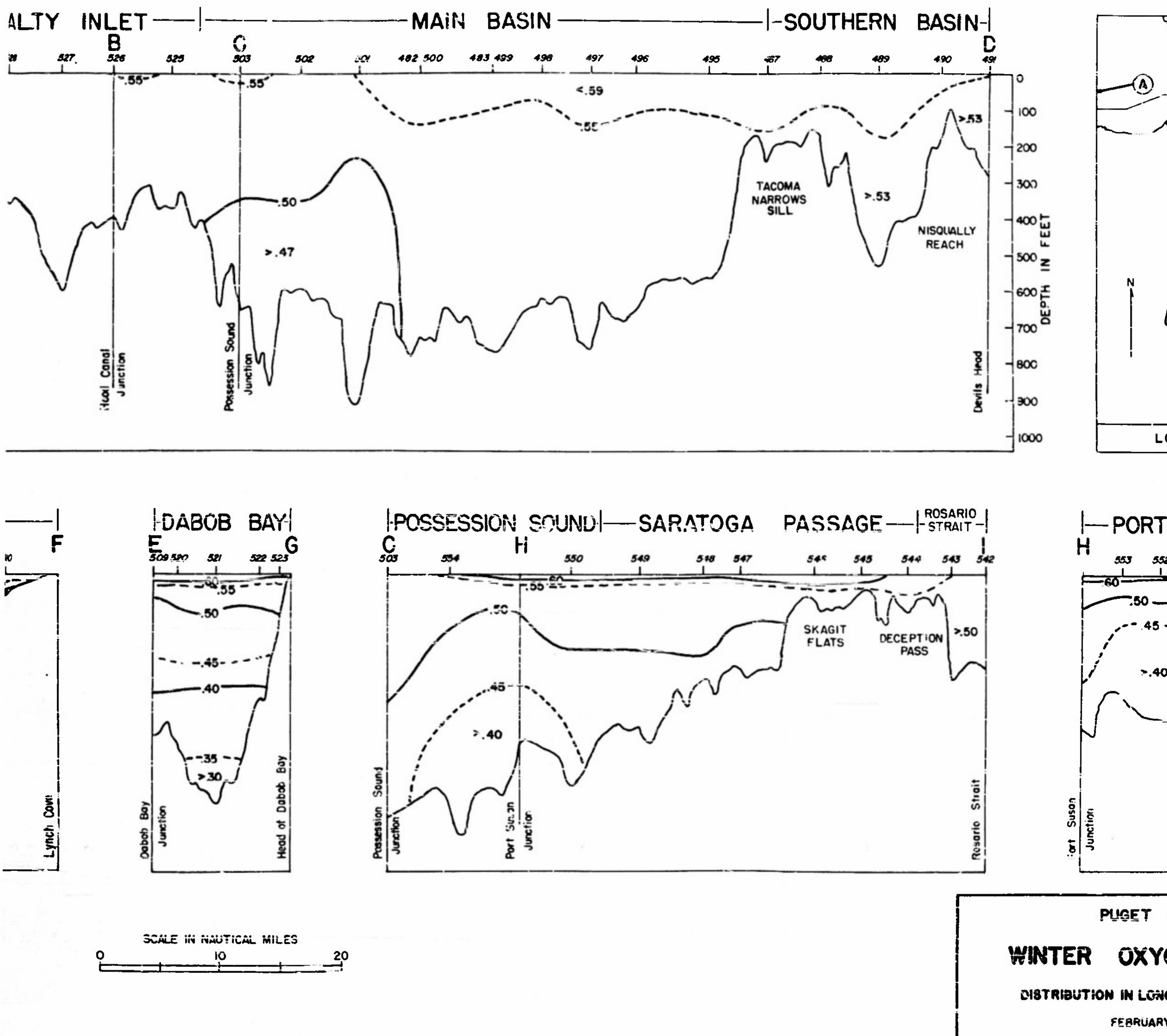
The winter dissolved oxygen distribution is shown in Fig. 10-23, and is similar to the summer condition. The oxygen content however has increased at depth and decreased in the surface layers. The pronounced summer oxygen sinks have disappeared except for the one in Dabob Bay and at the head of Lynch Cove. The oxygen concentration is higher in these areas indicative of the more active winter time circulation.

SOLUBLE PHOSPHATE DISTRIBUTION

The summer condition phosphate values are shown in Fig. 10-24. The summer oxygen and phosphate distribution patterns are very similar but the values are inversely related. As oxygen is used up, phosphate is liberated, so in general high phosphate concentrations are associated with low oxygen content. It is therefore possible to utilize the phosphate concentration along with the oxygen content to determine the approximate age of the water mass. For an additional discussion on phosphate see paragraph under Chemistry of Puget Sound Waters, this section.



STRAIT OF JUAN DE FUCA
ADMIRALTY INLET
A
B
C
STA. NO.
DEPTH IN METERS
VICTORIA-GREEN PT SILL
ADMIRALTY INLET SILL
Pillar Point
Hood Canal Junction
Possession Sound Junction
HOOD CANAL
SOUTHERN HOOD CANAL
DABOB BAY
D
E
F
G
ENTRANCE SILL
Hood Canal Junction
Dabob Bay Junction
Lynch Cove
Head of Dabob Bay
SCALE IN NAUTICAL MILES
0
10


ALTY INLET
MAIN BASIN
SOUTHERN BASIN
B
C
D
527
526
525
503
502
482 500
483 499
498
497
496
495
488
489
490
.55
<.59
>.53
.50
>.47
TACOMA
NARROWS
SILL
>.53
NISQUALLY
REACH
Hood Canal Junction
Possession Sound Junction
Devils Head
0
100
200
300
400
500
600
700
800
900
1000
DEPTH IN FEET
N
LO
F
Lynch Cove
DABOB BAY
E
G
521
522 523
.60
.55
.50
.45
.40
.35
>.30
Dabob Bay Junction
Head of Dabob Bay
POSSESSION SOUND
SARATOGA PASSAGE
ROSARIO STRAIT
C
H
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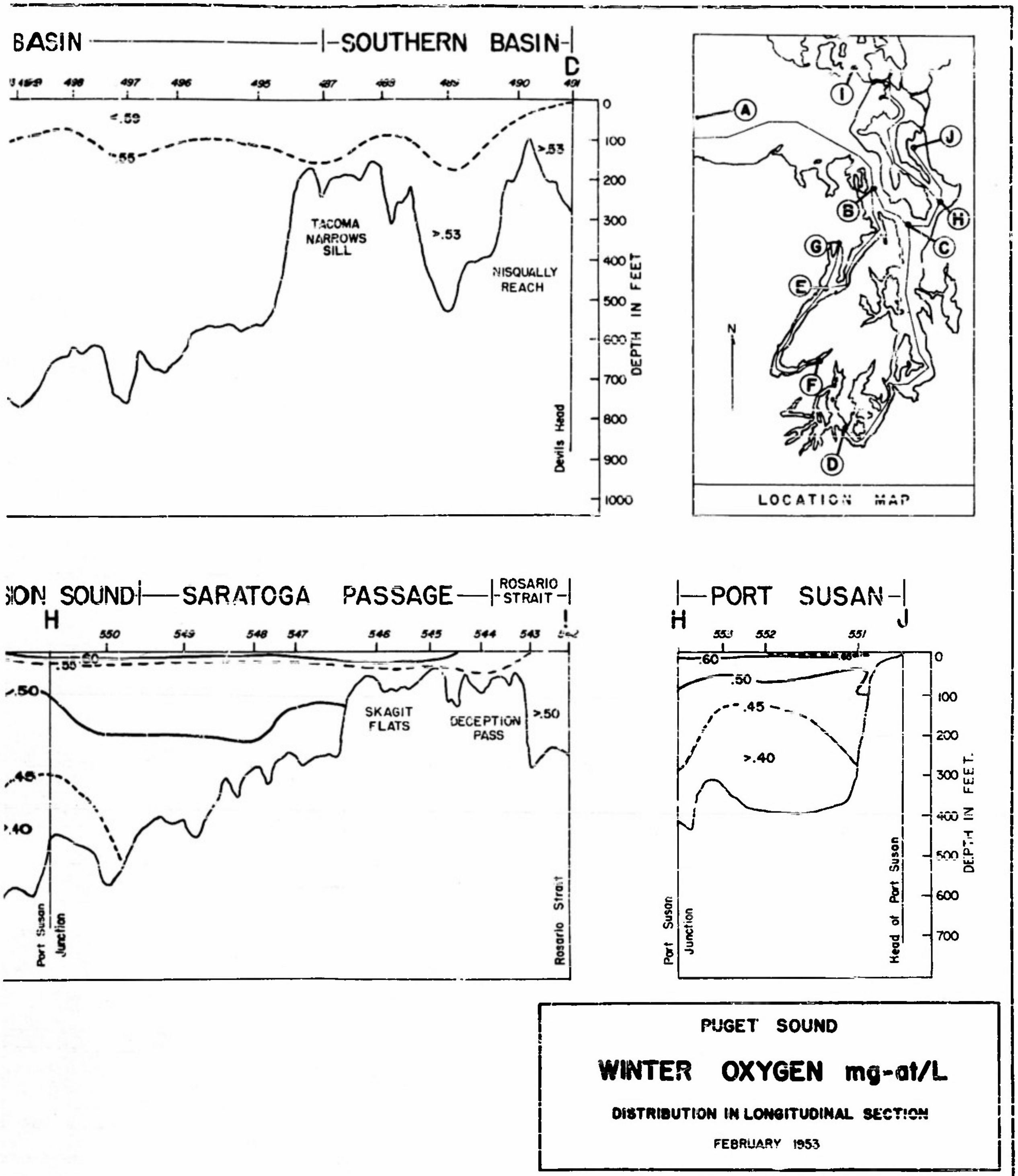
554
550
549
548
547
545
544
543
542
.60
.55
.50
.45
>.40
SKAGIT
FLATS
DECEPTION
PASS
>.50
Possession Sound Junction
Port Susan Junction
Rosario Strait
PORT
H
553
552
.60
.50
.45
>.40
Port Susan Junction
SCALE IN NAUTICAL MILES
0
10
20
PUGET
WINTER OXY
DISTRIBUTION IN LONG
FEBRUARY

Fig.10-23



BASIN
SOUTHERN BASIN
D
498
497
496
495
487
488
490
491
.55
>.53
TACOMA NARROWS SILL
>.53
NISQUALLY REACH
Devils Head
0
100
200
300
400
500
600
700
800
900
1000
DEPTH IN FEET
A
B
C
D
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F
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H
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J
N
LOCATION MAP
SOUND
SARATOGA PASSAGE
ROSARIO STRAIT
H
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548
547
546
545
544
543
.60
.55
.50
SKAGIT FLATS
DECEPTION PASS
>.50
.45
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Port Susan Junction
Rosario Strait
PORT SUSAN
H
J
553
552
551
.60
.50
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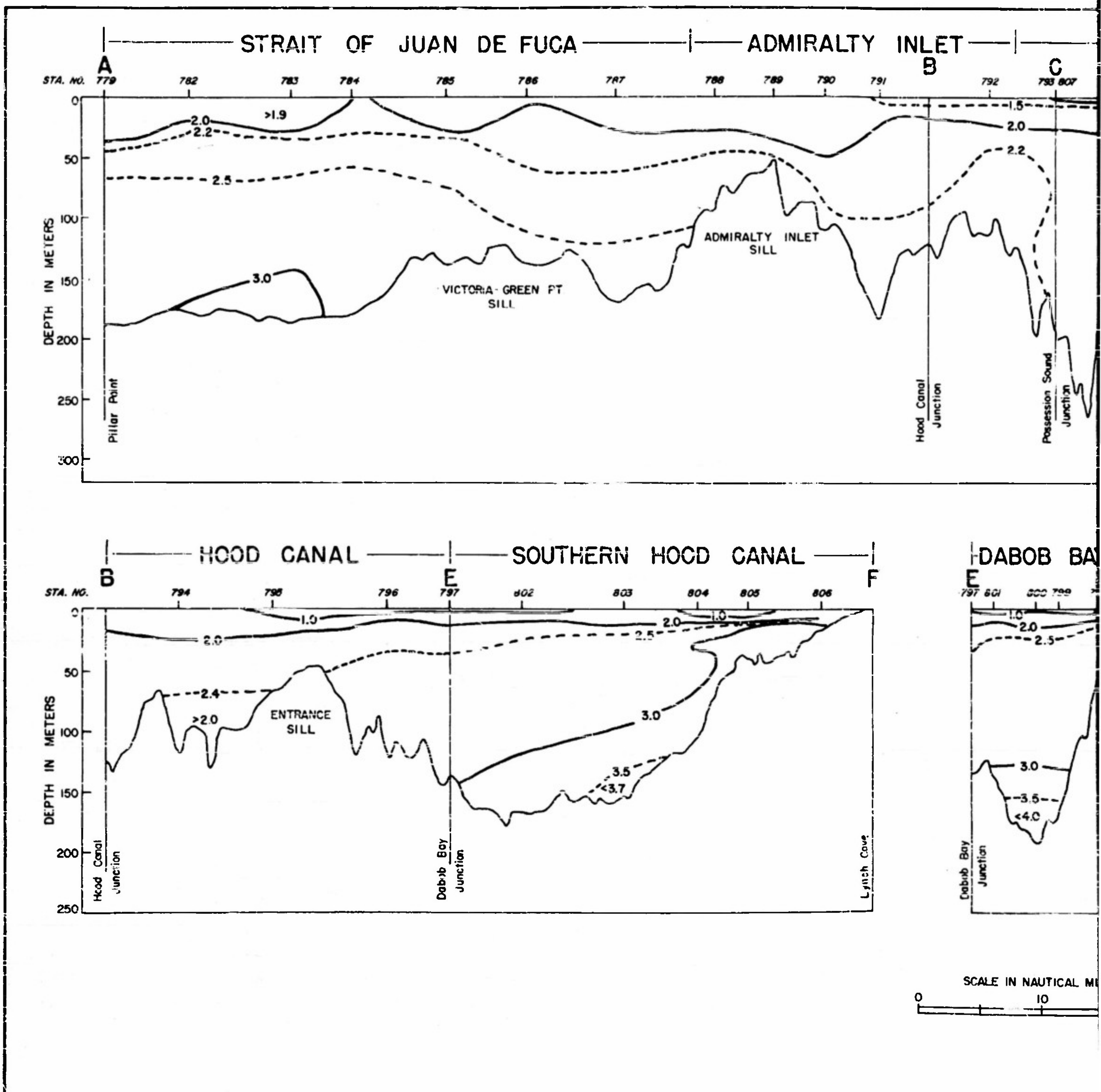
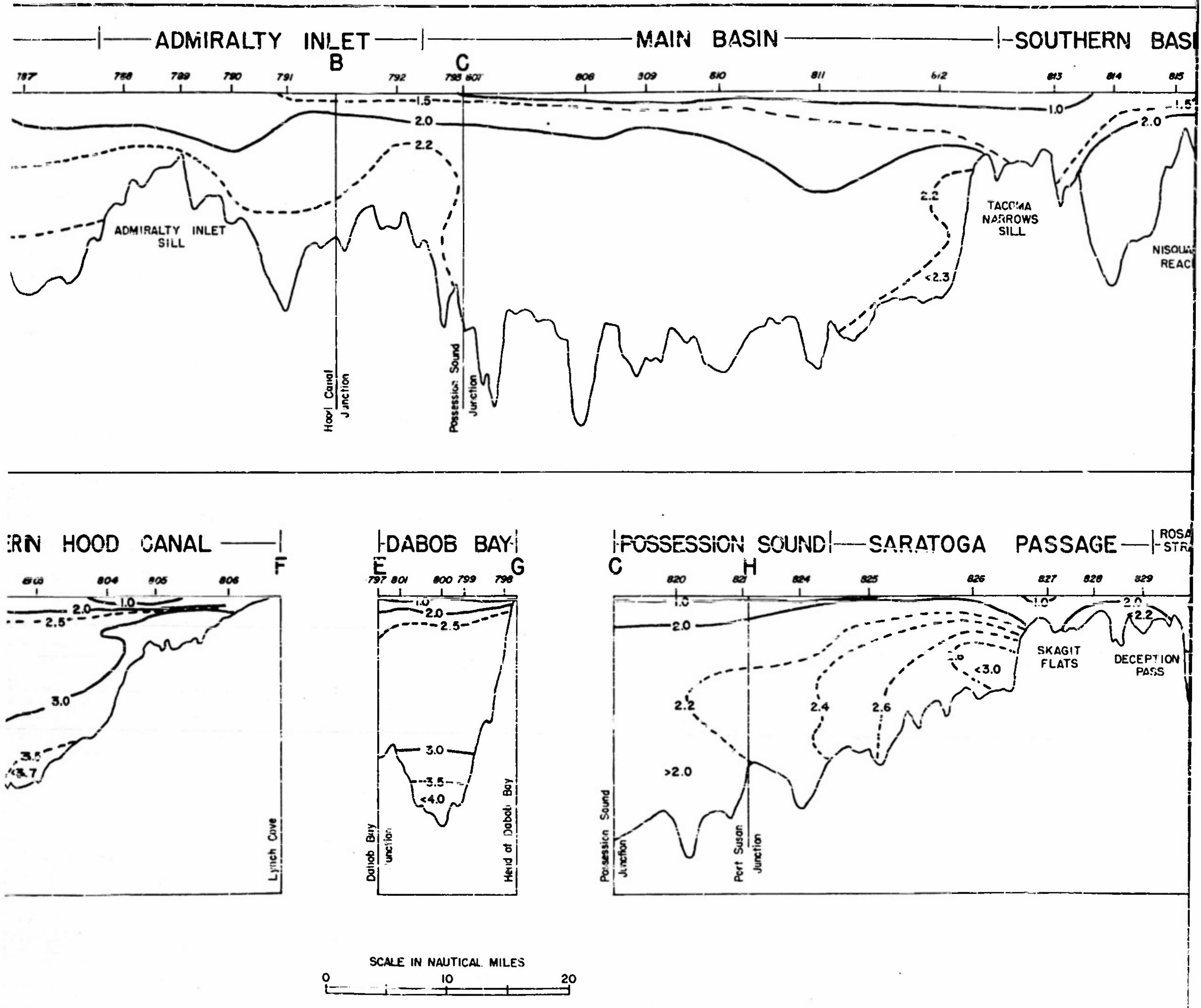
Port Susan Junction
Head of Port Susan
0
100
200
300
400
500
600
700
DEPTH IN FEET
PUGET SOUND
WINTER OXYGEN mg-at/L
DISTRIBUTION IN LONGITUDINAL SECTION
FEBRUARY 1953

Fig. 10-23



STRAIT OF JUAN DE FUCA
ADMIRALTY INLET
A
B
C
STA. NO.
779
782
783
784
785
786
787
788
789
790
791
792
DEPTH IN METERS
>1.9
2.0
2.2
2.5
3.0
1.5
VICTORIA - GREEN PT SILL
ADMIRALTY INLET SILL
Pillar Point
Hood Canal Junction
Possession Sound Junction
HOOD CANAL
SOUTHERN HOOD CANAL
DABOB BA
E
F
794
796
797
802
803
804
805
806
1.0
2.4
>2.0
ENTRANCE SILL
3.5
<3.7
<4.0
Hood Canal Junction
Dabob Bay Junction
Lynch Cove
SCALE IN NAUTICAL MI
0
10



ADMIRALTY INLET
MAIN BASIN
SOUTHERN BAS
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793 801
808
809
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811
812
813
814
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1.5
2.0
2.2
1.0
ADMIRALTY INLET SILL
TACOMA NARROWS SILL
NISQUA REAC
<2.3
Hood Canal Junction
Possession Sound Junction
ERN HOOD CANAL
F
803
804
805
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Lynch Cove
DABOB BAY
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797 801
800 799
798
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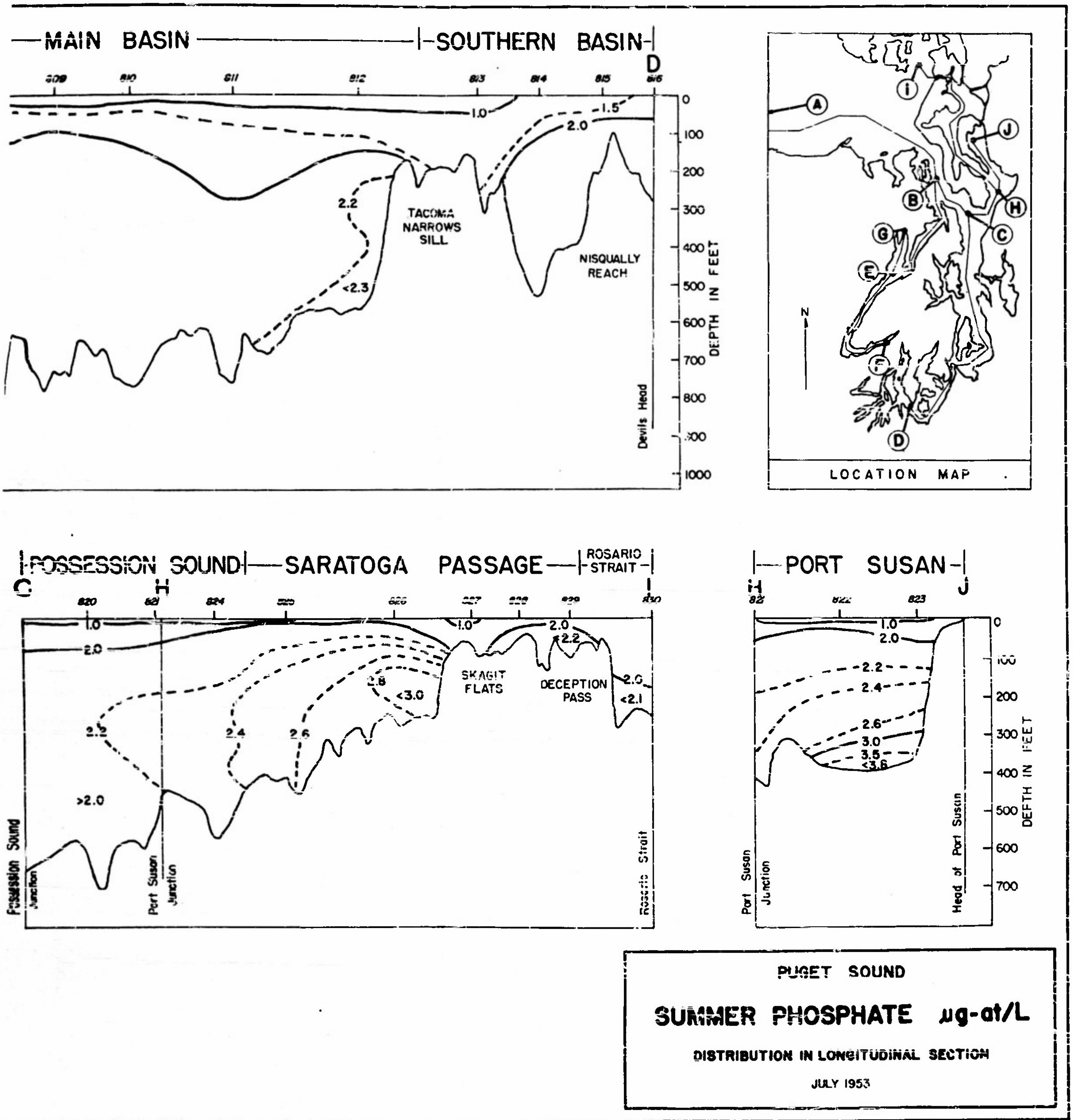
<4.0
Dabob Bay Junction
Head of Dabob Bay
POSSESSION SOUND
SARATOGA PASSAGE
ROSA STR
H
820
821
824
825
826
827
828
829
2.4
2.6
<3.0
>2.0
SKAGIT FLATS
DECEPTION PASS
Possession Sound Junction
Port Susan Junction
SCALE IN NAUTICAL MILES
0
10
20



MAIN BASIN
SOUTHERN BASIN
D
TACOMA NARROWS SILL
NISQUALLY REACH
Devils Head
DEPTH IN FEET
LOCATION MAP
POSSESSION SOUND
SARATOGA PASSAGE
ROSARIO STRAIT
SKAGIT FLATS
DECEPTION PASS
Possession Sound Junction
Port Susan Junction
Rosario Strait
PORT SUSAN
Head of Port Susan
PUGET SOUND
SUMMER PHOSPHATE µg-at/L
DISTRIBUTION IN LONGITUDINAL SECTION
JULY 1953

Fig. 10-24

CHEMISTRY OF PUGET SOUND WATERS

INTRODUCTION

The Puget Sound region offers an excellent opportunity for the study of the physical and chemical characteristics of sea water under remarkably different conditions. There are many estuaries with rather varied topographies in the Sound proper, while among the San Juan Islands are many lagoons of interesting formation. A number of rivers flow into the Sound and produce local areas that show wide seasonal variation and offer excellent opportunity to study changes produced in sea water as the result of natural dilution.

An upwelling of ocean water during the summer months apparently occurs off the coast of the state of Washington, analogous in some respects to the waters off the California coast, within the Strait of Juan de Fuca vertical turbulence accompanying the strong tidal currents actively admixes the upwelled water to the surface. It is this upwelled water, rich in nutritive material, that largely comprises the deep water of Puget Sound and adjoining regions. Evidence of this upwelling is shown particularly in the phosphate content of the water but may likewise be shown by the study of other nutritive material (Thompson, McCorkell, and Bonnar 1930; Igelsrud, Robinson, and Thompson 1936).

DILUTION AND IONIC RATIOS

Waters of the area vary considerably as to dilution--however, the major constituents of sea water are always in the same proportion to one another, except possibly, in very highly diluted waters. Knowing the ionic ratio of a given major constituent, the concentration of that constituent may be obtained by multiplying the chlorinity or the chlorosity by the ionic ratio. Thus, for example, the ionic ratio for the sulfate/chloride ion is 0.1392. If a sample of sea water has a chlorinity of 16.75 $^{0}/_{00}$, the sulfate concentration of this water will be 2.332 grams per kilogram of sea water. This same water has a chlorosity of 17.10 grams per liter and the sulfate concentration per liter at 20° C. would be 2.380 grams per liter.

CONCENTRATION OF CHEMICAL CONSTITUENTS

Values for the concentrations and distribution of the following elements and ions have been determined and summarized for Puget Sound.

- Alkalinity
- Aluminum
- Ammonia
- Boron
- Bromine
- Calcium
- Carbon Dioxide
- Copper
- Fluorine
- Gold
- Hydrogen Sulfide
- Iodine
- Iron
- Isotopic or Heavy Water
- Magnesium
- Manganese
- Nitrate
- Nitrite
- Nitrogen
- pH or Hydrogen Ion
- Phosphate
- Potassium
- Radium
- Silicate
- Sodium
- Strontium
- Sulfate
- Titanium
- Uranium

Alkalinity

The expression alkalinity or alkalinity of sea water is used to designate the normality, in terms of milliequivalents, of the marine water as a base, the equivalent point being that at which the bicarbonate and carbonate ions have been converted to carbonic acid. Thus, any constituent of marine water, silicates, borates, or any ion capable of reacting with the hydrogen ion in solution, will be included in the alkalinity provided only that it reacts at a pH above that encountered in the conversion of the bicarbonate to carbonic acid.

Over 1,400 analyses made of samples collected at regular stations in Puget Sound and adjacent waters have been analyzed for alkalinity in the data presented here. The alkalinity-chlorinity ratio in milliequivalents of base to chlorinity has been accepted as 0.125 for Puget Sound. Averaged values ranged from 0.115 to 0.135 for Puget Sound and approaches. Two Pacific Ocean stations showed an average alkalinity-chlorinity ratio of 0.121 (Anderson 1943).

Alkalinity for surface samples from Hood Canal range from 1.160 to 2.171 with alkalinity-chlorinity ratios from 0.125 to 0.230. Data from the Nisqually Flats show alkalinities from 1.860 to 2.213 with alkalinity-chlorinity ratios from 0.124 to 0.171.

Ammonia

One hundred and ninety-three free ammonia analyses were made between June 30 and July 7, 1932, on a trip from Friday Harbor to the southern part of Puget Sound. Of these, 188 showed no ammonia (that is, less than 1.43 microgram-atoms of ammonia nitrogen per liter), four showed 1.43 microgram-atoms, and one 9.30 microgram-atoms of ammonia nitrogen per liter. The 188 samples

showing no ammonia were taken at the surface, 10, 25, 50, 100, 150, and 200 meters. Three of the samples containing 1.43 microgram-atoms per liter were from one station off Foulweather Bluff at the entrance to Hood Canal, at depths of 25, 50, and 100 meters. Only one surface sample showed ammonia. The sample containing 9.30 microgram-atoms was a bottom sample from East Sound (Robinson and Wirth 1934b).

Aluminum

The concentration of aluminum in sea water from Friday Harbor and various depths in the waters of the northeast Pacific Ocean has been determined. The concentration of aluminum varies with depth, there being a slight increase in the region approaching 1,000 meters, that region in which high iron and very low oxygen values were also found.

For aluminum content in the waters of the San Juan Islands monthly averages showed a slight tendency to higher values in the early spring months and extended into June. The values for the San Juan area were lower than those for the deep sea samples obtained.

The concentration of aluminum in sea water averages, for all samples, seasonal and depth, 20 microgram-atoms per liter, or 0.54 milligrams per liter. The average value for samples in the San Juan area was 11.0 microgram-atoms per liter, ranging from a minimum value of 6.0 microgram-atoms per liter to a maximum value of 24.0 microgram-atoms per liter (Haendler and Thompson 1939).

Boron

Boron, as soluble borate, was determined in 377 samples of sea water from the coastal waters of the northeast Pacific Ocean including the San Juan Island area. The amounts varied between 0.128 and 0.497 milligram-atoms per liter of sea water but were always proportional to the chlorinity of the waters. The ratio boron chlorinity as milligram-atoms of boron to chlorinity was found to be 0.0223. Concentrations of boron appear to vary with depth and tidal cycle.

For coastal waters within Dixon Entrance, Alaska, and Hecate Strait, British Columbia, the average boron-chlorinity ratio was 0.0227.

The discrepancy between the amounts of boron reported as found in sea water by different analytical methods and investigators is pointed out with the suggested explanation that complex boron compounds may account for the irregularities, as well as for the small deviations observed in the boron-chlorinity ratios.

That soluble complex boron compounds may exist in sea water is indicated by the fact that marine animals and plants contain boron which upon the death and decay of such organisms is returned to the sea water.

Analyses of five species of marine algae gave 4.2 to 14.9 milligram-atoms boron per kilogram of dried material or 15.1 to 50.3 milligram-atoms boron per kilogram of ash.

No accumulation of boron, beyond that observed in terrestrial plants growing in good soils low in boron, was observed in any of the species of marine plants examined.

Boron was found in amounts of 20.8 and 80.0 milligram-atoms per kilogram in samples of Conus and Cyprea and 173 milligram-atoms per kilogram in a sample of Hydrocorallina. These results indicate that boron might occur quite generally in calcareous and sedimentary structures of oceanic origin. It is suggested that the boron in these forms may be combined as magnesium or calcium borates (Igelsrud, Thompson, and Zwicker 1938).

Bromine

The bromine content of sea water in Puget Sound and adjacent waters has been determined. For two stations in Puget Sound, Point No Point and off Port Townsend, the bromine content varies from 0.0570 ‰ to 0.0590 ‰ (grams of bromine per kilogram of sea water). The increase in bromin concentration, in this instance, reflects an increase in depth of water. Under similar conditions the bromine concentration of water from the Strait of Juan de Fuca exhibits concentrations, increasing with depth, of 0.0606 ‰ to 0.0648 ‰.

It has been shown that the bromine concentration of sea water is proportionately related to the chlorinity of the water, the value ‰ bromine to chlorinity being 0.0034. Thus, Puget Sound having less saline water than the open ocean has a smaller concentration of bromine (Thompson and Korpi 1942).

Calcium

The concentration of calcium in the waters of Puget Sound has been determined from several locations. Additional values were obtained from the adjacent San Juan Island area. The values for Puget Sound range from 8.20 to 9.05 milligram-atoms per liter. Values for the San Juan area reached 9.39 milligram-atoms per liter (Thompson and Wright 1930).

The ratio of calcium to chloride, in ‰ calcium to chlorinity is 0.0215. This ratio does not vary more than 0.0002 for all waters studied.

Carbon Dioxide

During the summers of 1936 and 1937 samples of surface sea water were collected from San Juan Channel in the San Juan Islands. The concentration of total carbon dioxide was largely a function of the chlorinity of the water and varied from 1.76 to 2.04 milligram-atoms of carbon per liter. The high values for total carbon dioxide were accompanied by low concentrations of dissolved oxygen, higher chlorinities and lower temperatures, characteristics of the sub-surface water of the Pacific (Hamm and Thompson 1941).

Copper

The concentration of copper in the surface waters of San Juan Channel, Washington, was determined periodically over a period of seventeen months. The average concentration of copper in all samples analyzed was 0.023 microgram-atoms per liter. A definite seasonal trend was indicated with an autumn minimum of 0.016 microgram-atoms per liter of copper and a summer maximum of 0.028 microgram-atoms per liter. The copper content of the water varied inversely with the values obtained for water density, phosphates, and silicates.

The concentration of copper in the waters of East Sound, Washington, was determined during the summers of 1952 and 1953. The range of copper concentration was found to be from 0.018 to 0.13 microgram-atoms per liter with an average value of 0.035. The concentration of copper decreased with increasing depth in stratified water with little or no turbulence. In general, the copper concentration of the surface water showed an increase toward the head of East Sound. The very high concentration of copper, 0.13 microgram-atoms per liter, observed near the head of the Sound was explained as the result of an oxidizing and leaching process of the sediments in shallow waters or areas exposed to the air at low tides.

Analyses for copper gave fairly constant concentrations of copper, 0.023 microgram-atoms per liter, in the surface waters except for higher results obtained in the Seattle-Tacoma area of Puget Sound proper. It was postulated that this high concentration of copper might arise from the industrial pollution and contamination of the surface water by the cities (Chow and Thompson 1954a, 1954b).

Fluorine

The average fluoride content of the waters of the Pacific Ocean near the state of Washington and the inland sea waters nearby is about 0.066 milligram-atoms of fluorine per liter of sea water. It ranges from 0.053 to 0.074 milligram-atoms per liter and shows no seasonal fluctuations, but increases with depth until approximately uniform conditions of salinity are encountered and a constant fluorine to chlorinity ratio is established.

An increase in fluoride content over that of the open ocean has been noted for "inside" waters such as straits, sounds, bays, and inlets. The increase in the fluoride-chlorinity ratio (fluoride in milligram-atoms per liter) from 3.6×10^{-3} for the open ocean to 3.8×10^{-3} for Puget Sound water is indicative of this trend (Taylor 1932; Thompson and Taylor 1933).

The aluminum and fluoride ion content of sea water is in approximately the same proportion as aluminum and fluorine in the mineral cryolite (Na_3AlF_6).

Gold

The amount of gold in sea water is not nearly as great as reported in most texts or in popular literature. It is conceivably present in sea water in one of the following states: auric or aurous ion, colloidal gold particles, gold entrained in or comprising part of suspended rock particles, organic gold-containing matter. Numerous investigators have analyzed sea water for its gold content, and much variance is noted in their results.

Caldwell analyzed sea water from Puget Sound and adjacent waters including samples from the coast of Oregon and reported values ranging from 0.1 to 1.0 milligrams of gold per metric ton of sea water (Caldwell 1938).

Hydrogen Sulfide

There are no known areas in Puget Sound that contain permanent hydrogen sulfide pockets. Occasionally pockets will develop near the head of some inlets where anaerobic conditions occur.

While not in Puget Sound proper, Lake Union and other portions of Lake Washington Ship Canal will develop high concentrations of hydrogen sulfide (Smith and Thompson 1927a; Seckel 1953).

Iodine

Samples of sea water from the San Juan and Strait of Juan de Fuca region have been analyzed for iodine. In general, the amount of iodine has been found to increase as the Pacific Ocean is approached and with the depth at which the sample is taken. Waters containing large amounts of plankton, such as East Sound, were found to be somewhat lower in iodine content. In many cases samples taken near the bottom were found to be slightly lower in iodine content.

For surface waters iodine concentrations range from 0.355 to 0.670 microgram-atoms per liter which span all values obtained except that for the maximum station which reached a concentration of 0.725 microgram-atoms per

liter. The average for all stations in the area is 0.473 microgram-atoms per liter (Evans 1932).

Another study for iodine concentrations was made which duplicated the area covered by Evans and included values for southern Puget Sound. These values are, however, extremely high and variable. Because of their inconsistency these values will not be quoted (Bonnar 1931).

Iron

The iron content of the water increases with depth and its concentration is materially affected in passages where there is marked turbulence of the waters. A two-year investigation and examination of surface samples collected in the San Juan Island area has shown seasonal variations in iron content of sea water. Unfiltered samples were analyzed for total iron and filtered samples for soluble iron.

Fluctuations may be attributed to a number of causes, such as the rate of discharge of large rivers affecting the region over a large area, the local runoff in the immediate region due to rains, the quantities of suspended material carried into the water by drainage, the nature and height of waves beating upon the shores of the region, the strength of the tidal currents which would create a turbulence and thus carry into the supernatant waters fine materials previously deposited on the bottom, and also the variation in tidal conditions during a given month.

The data show a large degree of parallelism between the total and soluble iron content. Both rise to a maximum during the winter months and fall to a minimum during the summer. The most rapid decrease in iron content occurs during the latter part of March and the principal increase occurs during September and October. The average spring-summer and fall-winter values are as follows:

	Spring-Summer microgram-atoms/kilo	Fall-Winter microgram-atoms/kilo
Total Iron	0.53	1.47
Soluble Iron	0.26	0.75

(Thompson and Bremner 1935).

Isotopic or Heavy Water

It has been found that water from various natural sources differs slightly in density due presumably to varying content of H^2, O^{17}, and O^{18}. Further investigation has shown that there is a definite difference in density between water distilled from sea water and water distilled from tap

water. The difference in density (greater density for water distilled from sea water) is attributed to a larger concentration of heavy water (water containing the hydrogen isotope of mass two, or the oxygen isotope of mass eighteen) in the sea water than in tap water.

The average difference in density between water distilled from sea water and that distilled from tap water was found to be 1.37×10^{-6} for thirty-one samples of ocean water investigated. However, a region in the San Juan Archipelago, adjacent to Puget Sound, noted for its abundant fauna and flora, yielded waters of very low density differences of the order of 0.8×10^{-6}. This value is low even when account is taken of the fresh water dilution which has reduced the chlorinity to sixteen parts per thousand, and is proportionately lower than any other values found, especially from the Pacific Ocean which is the ultimate source of the sea water in the area (Wirth 1934; Wirth, Thompson, and Utterback 1935).

Magnesium

The concentration of magnesium in the waters of Puget Sound has been determined from several locations. Additional values were obtained from the adjacent San Juan Island area. The values for Puget Sound range from 1.034 to 1.147 grams per liter, being proportional to the chlorinity of the water. Values for the San Juan area reached 1.163 grams per liter. The magnesium-chloride ratio, grams per liter magnesium to chlorinity, was found to be 0.0669 (Thompson and Wright 1930).

Manganese

The manganese content of sea water has been found to vary from 0.02 to 0.18 microgram-atoms per kilogram of water. Analysis of water from Puget Sound and closely adjacent areas shows a range in manganese content of 0.05 to 0.15 microgram-atoms per kilogram of water.

The manganese content of bottom muds in Hood canal has been found to vary from 0.06 °/o to 0.28 °/o (of dry sample) or 10.9 to 50.9 milligram-atoms per kilogram of dry mud.

The manganese content of some of the shells of organisms native to Puget Sound was found to vary from 0.003 to 0.007 °/o (of dry weight), equivalent to from 0.5 to 1.2 milligram-atoms per kilogram of dried material (Thompson and Wilson 1935).

Nitrate

Nitrate, though present in very small amounts, plays an important role in the sea. Several series of sea water samples were collected from the

Pacific Ocean and from East Sound and San Juan Channel in the San Juan Islands for analysis by a new method (Chow and Robinson 1953). Nitrate concentration as nitrate-nitrogen for East Sound ranged from 0.0 to 0.5 microgram-atoms per liter, values increasing with depth. For San Juan Channel, values ranged from 9.6 to 13.4 microgram-atoms per liter and for the Pacific Ocean samples values ranged from 6.5 to 47.2 microgram-atoms per liter, values increasing with depth.

In East Sound, essentially a long, narrow inlet without a threshold, there is a relatively slow exchange of water with the adjoining bodies; also, East Sound waters are stratified during the summer months. At the time of sampling, its water supported an abundant diatom population which rapidly depleted the water of nitrate

The waters of San Juan Channel are rather uniform in distribution because of vertical mixing; the water itself shows the effect of dilution by the Fraser River water during the months of early summer.

The ocean station offered deep samples that were rich in nitrate and surface samples with reduced nitrate concentrations (Chow and Robinson 1953).

In general nitrate distribution has been found to be the same as that of the phosphate. The bottom layers showed a range for the inside waters of 14.6 to 29.3 microgram-atoms nitrate nitrogen per liter while in the photosynthetic zone regional variations were observed. In those waters affected by rivers and where photosynthetic activity was most marked, the nitrates would be entirely depleted, while, on the other hand, mixing of the waters would result in a vertical homogeneity (Thompson and Robinson 1934).

Nitrite

Nitrite nitrogen was found to be very low or absent in the deeper layers of water off Cape Flattery, while the surface layers and most other waters in the region were found to be particularly rich. In the Strait of Juan de Fuca, in general, nitrites increase with depth to a maximum value of about 0.50 to 0.57 microgram-atoms of nitrite nitrogen per liter at 25 meters and then decrease to practically zero as the bottom is approached. In the Gulf of Georgia and the waters adjacent to the San Juan Islands the amount of nitrite was lower and increased with depth to a maximum of 0.29 microgram-atoms per liter at the bottom. The increase in nitrite with depth in this case is due to the dilution of the surface layers of water to a greater extent than the deeper layers by the waters of the Fraser River. Most of the waters investigated contained some nitrite, indicating that the process of nitrification was taking place (Evans 1932).

For Puget Sound proper, as determined from an extended cruise in 1933, the nitrites follow the same general curve as the phosphates, except in the

Hood Canal area where zero values were obtained throughout. In all of the localities where there was a very marked plankton growth the nitrites were absent (Thompson and Phifer 1936).

Nitrites are seldom found at any depth in Hood Canal but in other regions of Puget Sound values for nitrite nitrogen ranging from 0.29 to 0.43 microgram-atoms per liter were frequently observed. As a rule the nitrites increased with depth to 25 to 50 meters when maximum concentrations were obtained. At stations off the Washington and Vancouver Island coasts, no nitrites were detected except at 25 and 50 meters (Thompson and Robinson 1934).

Nitrogen

Analyses for both albuminoid and organic nitrogen were made in the Puget Sound area. Of the samples on which both analyses were made the average value for albuminoid nitrogen was 7.15 microgram-atoms per liter and 15.0 microgram-atoms per liter for organic nitrogen. The average ratio of albuminoid nitrogen to organic nitrogen is 0.47.

The average organic nitrogen content decreases with depth. Only slight variation in the amount of organic nitrogen was found between different localities. The average amount of organic nitrogen was 12.1 microgram-atoms per liter. In East Sound the average was 13.6 microgram-atoms per liter over a two-year period with little variation between three different stations. Hood Canal, which in many respects is similar to East Sound, had an average of 10.0 microgram-atoms per liter, while the Strait of Juan de Fuca which is in direct communication with the Pacific, had an average of 10.7 microgram-atoms of organic nitrogen per liter. The average for Eld and Totten Inlets was the highest found for any region, with 17.9 microgram-atoms per liter.

An attempt was made to determine the distribution of total combined nitrogen, that is, the sum of nitrate and organic nitrogen, as the free ammonia and nitrite are too scarce in comparison to influence the result. On account of the unreliability of the absolute values of nitrate only approximate conclusions can be drawn.

The largest average amount of total nitrogen was 31.4 microgram-atoms per liter for the Strait of Juan de Fuca. Since the organic nitrogen for this locality was average, the larger value for total nitrogen depended upon the larger amount of nitrate. The results of the other localities were smaller and quite regular: 20.7 microgram-atoms for Hood Canal, 22.1 microgram-atoms for Eld and Totten Inlets, and 24.3 microgram-atoms of total nitrogen per liter for East Sound.

Although for a given body of water it might be supposed that the total nitrogen content would be more or less constant, considerable fluctuation

was apparent for the average amount among various stations, varying from 12.9 microgram-atoms in Hood Canal to 42.1 microgram-atoms per liter in the Strait of Juan de Fuca (Robinson and Wirth 1934b).

pH or Hydrogen Ion

During the summers of 1918 and 1919 pH observations in the San Juan Islands showed a range of 7.77 to 8.17 for surface waters. At this same time determinations made for water at different depths in the San Juan area indicated no uniformity with the variation of the hydrogen ion concentration and depth.

The pH values found for Argyle Lagoon, near Friday Harbor, showed a range of 7.89 to 8.62. It was also found that the pH in sea water vegetation in the San Juan Islands ranged from 7.72 to 9.3 (Powers 1920).

It has been noted that the pH found in oyster beds in southern Puget Sound range from 7.70 to 7.95 at the mouth of a stream and in lagoons is above 8.8 (Thompson and Bonner 1931).

Based upon a cruise made in 1933 the lowest pH values were obtained in the waters of the San Juan Archipelago with the exception of one sample which was taken near the mouth of the Skagit River and had an exceedingly low chlorinity. The highest values were observed in Skagit Bay, Saratoga Passage, and at the head of Hood Canal. The pH values obtained, uncorrected for salt error, varied from 7.90 to 8.80, using cresol red as the indicator (Thompson and Phifer 1936).

Phosphate

The waters of the Puget Sound region are very rich in phosphates, the result of upwelled ocean water. The high phosphate concentration cannot be attributed to river discharge (Thompson, McCorkell, and Bonnar 1930).

Sea water samples collected in Dabob Bay, Puget Sound were analyzed for phosphates. The inorganic phosphate concentration increased with depth, as is usually the case with stratified waters. The organic phosphorus values showed no definite correlation with depth. The inorganic phosphorus ranged from 0.66 to 3.07 microgram-atoms per liter and the organic phosphorus ranged from 0.32 to 0.59 microgram-atoms per liter (Hansen and Robinson 1953).

Based upon an extensive cruise made in 1933, phosphate values were obtained that ranged from 0 to 1.28 microgram-atoms of phosphorus per liter. It was found that on entering Skagit Bay from Deception Pass an unusually high value for phosphate was obtained near the mud flats and in the same locality where abnormally low chlorinity values were found. The phosphate ratio for this station was considerably greater than that obtained for ordinary sea

water, and therefore indicates that the sources of phosphate must have been other than sea water. This has been explained by the fact that though the fresh waters of the Skagit River show only a mere trace of phosphates, they discharge into the sea over extended mud flats and leach the phosphate from decaying organic matter periodically exposed to the air. In other portions of Skagit Bay, Saratoga Passage, and Possession Sound, as well as in Hood Canal, the surface water was devoid of inorganic phosphorus. Marked fluctuations in the concentration of the element were found in the waters of the other regions (Thompson and Phifer 1936).

Chow and Thompson (Chow and Thompson 1954a) in an examination of water collected in the mud flats of East Sound found an inorganic phosphorus concentration as high as 8.0 microgram-atoms per liter.

South of the Tacoma Narrows in Puget Sound, turbulence results in an even vertical distribution of the phosphates averaging during the summer months concentrations of 0.97 microgram-atoms of phosphorus per liter against that of 1.61 microgram-atoms during the winter months (Thompson and Robinson 1934). For an additional paragraph on phosphate see paragraph and seasonal profile under Water Mass Characteristics, this section.

Potassium

The concentration of potassium in sea water has recently been determined for numerous locations throughout the world as well as in Puget Sound. Values ranged from 0.3278 °/oo (East Sound, Washington) to 0.4050 °/oo (Sargasso Sea). Values are found to increase with depth.

Off the coast of Washington values range from 0.3731 °/oo (100 meters) to 0.3871 °/oo (1,800 meters). At Hein Bank, Strait of Juan de Fuca values range from 0.3437 °/oo (surface) to 0.3563 °/oo (135 meters). Off Point Jefferson, Puget Sound values range from 0.3279 °/oo to 0.3342 °/oo between surface and 200 meters respectively (Jentoft 1952). The ratio of potassium-chlorinity has been found to be 0.02023 (Jentoft 1952).

Radium

The radium content of sea water has been measured from various locations in the world including the waters of the San Juan Archipelago. Values for the latter area range from 3.5×10^{-15} to 6.9×10^{-15} grams of radium per cubic centimeter of water. An average value of 5×10^{-15} grams of radium per cubic centimeter of water has been given.

It has been observed that radioactivity of Pacific Ocean water has a minimum value. Also that radioactivity increases with decrease in temperature of the water and with depth. The waters of the North Atlantic and of Hudson Bay show much higher values than Pacific water. Values for off the California

coast average 4×10^{-15}, Gulf of Alaska 7×10^{-15}, North Atlantic 43×10^{-15}, and Hudson Bay 45×10^{-15} grams of radium per cubic centimeter (Devaputra, Thompson, and Utterback 1932).

Measurements using more refined analytical methods have shown results several orders of magnitude lower than those obtained by previous workers. A value of 6×10^{-17} grams of radium per cubic centimeter water has been established for water in the San Juan area (Evans, Kip, and Moberg 1938).

Also see Geology Section, paragraph on Natural Radioactivity of Bottom Sediments.

Silicate

It has been shown that hydrographical interpretation is possible from dissolved silicon data for a given region. Dissolved silicate varies with tidal currents and with plankton abundance. Because of these variations it is not possible to calculate the silicon content of water from a ratio, such as chlorinity.

It may be further noted that silicate content increases with depth in most series of observations and that ocean waters have much lower silicate content than water of sounds, straits, and bays. The silicate content for waters of the San Juan area is extremely high. Values obtained for surface waters are only duplicated in magnitude at Monterey and La Jolla at depths of 50 to 100 meters.

Actual values for silicate content in the waters of the San Juan Islands and the Strait of Juan de Fuca range from 2.56 to 3.56 microgram-atoms per liter for the surface and reach 73.0 microgram-atoms per liter at 300 meters. The average silicate content for these waters is 3.56 microgram-atoms per liter.

In the inland waters of the Juan de Fuca Strait and the Puget Sound area, the silicates ranged from about 36.5 microgram-atoms of silicon per liter at the surface to 51.1 microgram-atoms per liter in the bottom waters. An exceptional growth of diatoms occasionally reduces the silicate content to 11.0 to 14.6 microgram-atoms of silicon per liter in the upper layers and frequently the bottom waters in some localities would show as high as 73.0 microgram-atoms per liter of silicon (Thompson and Robinson 1934).

From an extended cruise made in 1933 very much the same trend was observed for silicates as for phosphates. Near the mouth of the Skagit River the effect of dissolved silicates in fresh water was very noticeable. Relatively high silicate values were also obtained at the head of Hood Canal. In sailing the length of the Canal on a flood tide the silicate values were found exceedingly low in spite of the discharge of the large number of rivers

into the Canal; while returning on an ebb tide, just a few hours later, silicate values were found very much higher. Observed values of silicates ranged from 13.3 to 74.0 microgram-atoms of silicon per liter of water (Thompson and Phifer 1936).

The effect of river dilution has been studied by theoretical calculations and actual observations. Much less silicon was found in the water than theoretically calculated. The silicon content of river water is nearly 500 percent higher than that of average sea water while sea water adjacent to river mouths is 20 percent lower in dissolved silicon than average sea water and nearly 700 percent lower than river water causing dilution (Houlton 1931). It may also be noted that the weighed average silicon content for river water in the northwest is 274 microgram-atoms per liter.

Sodium

The concentration of ocean water varies considerably from place to place but it has been shown that relative concentration of the ions to each other is remarkably constant. Sodium is by far the outstanding major cation and it would be supposed that its relative concentration, expressed as the sodium-chlorinity ratio, would be quite accurately known. However, specific areas will show variation from this constant as will be shown below.

The results of analyses of 45 samples from three Pacific Ocean stations have shown sodium content to range from 9.73 to 10.67 grams per kilogram of water. The mean sodium-chlorinity ratio was calculated to be 0.5549. The results of analyses from 53 samples from seven stations located in the Strait of Juan de Fuca and Puget Sound show sodium content to range from 8.98 to 10.42 grams per kilogram of water, with the exception of one sample (Brown Point, surface, for which the Na $^{0}/_{00}$ was 7.24). The mean sodium-chlorinity ratio for these samples was found to be 0.5562. The mean value for the 98 samples analyzed is 0.5556 (Robinson and Knapman 1941).

Strontium

Values for the concentration of strontium in the waters of the San Juan Archipelago have been determined from composite water samples. For surface waters, 77.1 microgram-atoms per liter, and for a depth of 175 meters the strontium concentration was found to be 80.4 microgram-atoms per liter.

For comparative purposes, values found in analyses of Beaufort Sea water range from 68.6 microgram-atoms per liter for surface water and 93.1 microgram-atoms per liter for waters below 2,000 feet. Average strontium concentration for all waters is considered to be 91.3 microgram-atoms per liter (Burtner 1951).

Recent work conducted in 1953 and 1954 has shown strontium concentration as follows (based on conversion of chlorinity to 19 $^{o}/oo$):

Pacific Ocean (offshore)	93 microgram-atoms per liter
Beaufort Sea	94 microgram-atoms per liter
Atlantic Ocean	94 microgram-atoms per liter
Friday Harbor, Wash. (surface)	95 microgram-atoms per liter

(Thompson, Burtner, and Chow 1954).

The work of Burtner (Burtner 1951) will be found to be comparable to the above when converted to a uniform chlorinity of 19 $^{o}/oo$.

Sulfate

The sulfate-chloride ratio in the waters of the North Pacific and Puget Sound regions is very constant (grams per liter sulfate to chlorinity equals 0.1392). It may very, however, in waters that are decidedly affected by land drainage and contain colloidal and suspended matter.

The range of sulfates, in grams of sulfate per liter of sea water, for Puget Sound proper varies from 1.966 to 2.397 grams per liter. The waters of the San Juan Islands show maximum content of 2.525 grams per liter while water in the North Pacific ranged from 2.419 to 2.714 grams per liter.

The Skagit River which enters the northern portion of Puget Sound showed a high sulfate-chloride ratio of 9.08, with sulfate content of 17.71 milligrams per liter and a chlorinity content of 1.95 milligrams per liter (Thompson, Lang, and Anderson 1927). The sulfate ratio varies where there is marked anaerobic activity. See paragraph on Hydrogen Sulfide.

Titanium

Seven surface samples from Puget Sound and one from the Pacific Ocean were analyzed for titanium. Most samples showed only trace quantities, though one sample was found to have 0.02 microgram-atoms of titanium per liter of sea water. Analysis for a station at Point Jefferson in Puget Sound show that there is no significant increase in titanium content with depth.

Titanium was found to amount to 0.0021 $^{o}/o$ to 0.052 $^{o}/o$ (of dry sample) for diatoms and 0.20 $^{o}/o$ (of dry sample) for sea muds found locally (Griel and Robinson 1952).

Uranium

Sea water samples from Puget Sound and the Pacific Ocean have been analyzed for uranium content. Values for Puget Sound surface water range from 0.94×10^{-9} to 1.5×10^{-9} grams of uranium per gram of water. For the Pacific Ocean, off Destruction Island, values for surface water range from 0.47×10^{-9} to 0.51×10^{-9} grams of uranium per gram of water. It was found that uranium content increases with depth of water. For the 1,000 meter depth, off Destruction Island, values range from 0.67×10^{-9} to 0.86×10^{-9} grams of uranium per gram of water.

The high uranium content of Puget Sound waters compared to those of the ocean could possibly be due to a comparatively large uranium content of the river waters flowing into the Sound (Hoekstra 1942). The accuracy of the method used may be questioned in the light of markedly improved methods developed in recent years.

OCEANOGRAPHIC RESEARCH AT THE UNIVERSITY OF WASHINGTON

PRESENT STUDIES

A four point program of oceanographic research is currently being undertaken in the Department of Oceanography of the University of Washington. In general, the program may be outlined as follows:

(1) To make a detailed oceanographic survey of Puget Sound and the Strait of Juan de Fuca. This survey includes studies of:
- (a) Water characteristics (physical and chemical properties of the waters).
- (b) Circulation within the Strait and Sound proper and exchange of water with contiguous water masses including the open ocean.
- (c) Biological consequences integrated with physical oceanography.
- (d) Characteristics of bottom sediments.

Factors as tidal effects, meteorological conditions and effects, effects of fresh water influx, and interchange with offshore waters are being considered.

(2) To make a general investigation of the oceanographic implications of radioactive substances. This study includes:
- (a) Determination of distribution and concentration of naturally occurring radioactive constituents of sea water and bottom sediments.
- (b) Investigating the possibility of using selected radioactive substances as a means of identifying and tracking water masses.
- (c) Investigating the use of selected radioactive substances (isotopes) as chemical, biochemical, biological, and microbiological tracers in oceanographic problems.

(3) Laboratory and field studies of the physical and chemical properties of sea water and sea salts in various phases, including sea ice, sea-salt nuclei in the atmosphere over the ocean, etc.

(4) Participation in oceanographic aspects of Naval and other exploring expeditions.

COLLECTION OF OCEANOGRAPHIC DATA

Oceanographic data has been collected in Puget Sound and approaches since 1932. The data falls into two groups, that collected from 1932 to 1942 aboard the motor vessel CATALYST, and that collected from 1948 aboard

the motor vessels ONCORHYNCHUS and BROWN BEAR. No data were obtained in the 5-year interval 1943 to 1947.

The CATALYST was a 75-foot research vessel that belonged to the former Oceanographic Laboratories of the University of Washington. In addition to the collection of temperature and salinity data, samples were analyzed for dissolved oxygen, phosphate, silicates, nitrites, hydrogen ion concentration, and alkalinity. Water was also collected on various occasions for the study of a number of other constituents of sea water. At many of the stations occupied, vertical net hauls were made for the collection of plankton.

Data have been collected at irregular intervals from 1948 to 1953 aboard the ONCORHYNCHUS, a 50-foot fishing type vessel. From 1952 oceanographic stations have been repeatedly visited at approximately one month intervals by the BROWN BEAR, a 110-foot research vessel operated by the Department of Oceanography of the University of Washington. Temperature, salinity, and oxygen samples have been collected. Phosphates have been collected from July 1953.

Former Method of Station Representation

Each station was given a number which designated its location according to an arbitrary system of geographic nomenclature. The area was designated by a digit in the thousands place, the region by a digit in the hundreds place, the division by a digit in the tens place, and the locality by a digit in the units place. A decimal digit indicated a particular station in the given locality.

Table 10-9 enumerates the positions and names of these stations in Puget Sound and approaches. The number of times each station was occupied for temperature and salinity measurements are indicated. Additional stations, not listed, were occupied for special projects.

Present Method of Station Representation

The present system of station numbers is based upon the latitude and longitude of that station. The first four digits represent the latitude followed by a solidus (/) and four more digits which represent the longitude. For example, a station at 47°44.4'N latitude and 122°25.4'W longitude will have a station number of 7444/2254. Many former station locations have been reoccupied, others have been altered slightly, and a few have been added. Table 10-10 enumerates the positions and names of present stations in Puget Sound. Former station numbers are listed where applicable.

TABLE 10-9. Former Oceanographic Stations Visited in Puget Sound and Approaches. Stations Occupied From 1932 to 1942.

STATION NUMBER	NAME (Nearest Landmark)	LATITUDE N.	LONGITUDE W.	TIMES OCCUPIED
2311.1	Seal Rock	48°25.3'	124°26.7'	7
2312.1	Pillar Point	48°18.2'	124°03.1'	97
2314.1	Angeles Point	48°12.7'	123°33.4'	3
2314.2	Race Rocks	48°17'	123°37'	1
2315.1	New Dungeness	48°12.1'	123°15.5'	1
2315.2	New Dungeness	48°13.5'	123°13'	1
2316.1	Strait of Juan de Fuca	48°24.6'	123°06'	1
2316.2	Hein Bank	48°21.6'	123°07.4'	2
2316.5	Eagle Point	48°26.6'	123°04.1'	1
2317.2	Strait of Juan de Fuca	48°15'	122°59.1'	2
2317.4	Smith Island	48°18.6'	122°55'	2
2318.1	Davidson Rock	48°23.7'	122°47.1'	2
2411.1	Point Wilson	48°08.8'	122°43.9'	1
2411.3	Port Townsend	48°08'	122°41.1'	120
2413.5	Point No Point	47°54'	122°28.7'	125
2413.6	Edmonds	47°50.9'	122°25.6'	2
2414.1	Apple Cove Point	47°49'	122°27'	2
2414.2	Point Jefferson	47°44.5'	122°25.4'	68
2414.3	Port Madison Bay	47°43.1'	122°30.9'	1
2415.1	West Point	47°39.8'	122°27.8'	16
2415.2	Alki Point	47°34.2'	122°26.9'	16
2415.5	N. Ent., Colvos Passage	47°30.6'	122°29.2'	3
2416.1	Pully Point	47°26.4'	122°23.8'	13
2416.3	S. Ent., Colvos Passage	47°21'	122°32.4'	1
2416.4	Head Carr Inlet	47°21.6'	122°39.9'	2
2416.5	Head Carr Inlet	47°22.7'	122°37.8'	1
2417.1	Brown Point	47°19.3'	122°27.8'	14
2417.2	Fosdick Point	47°15'	122°35.1'	14
2417.3	Carr Inlet, Green Point	47°17'	122°42.9'	7
2417.4	McNeil Island	47°11'	122°38.1'	11
2417.5	Nisqually Flats	47°07.2'	122°42.5'	14
2417.6	Devils Head	47°09.8'	122°46.2'	10
2418.1	Dickenson Point	47°10.5'	122°51.1'	2
2418.3	Pickering Passage	47°11.9'	122°55.5'	10
2418.4	Pickering Passage	47°16.2'	122°55.4'	8

TABLE 10-9. Former Oceanographic Stations Visited in Puget Sound and Approaches. Stations Occupied From 1932 to 1942 (continued).

STATION NUMBER	NAME (Nearest Landmark)	LATITUDE N.	LONGTITUDE W.	TIMES OCCUPIED
2418.5	Dougall Point	47°18.4'	122°51'	9
2418.6	Herron Island	47°16'	122°51.2'	7
2419.1	Henderson Inlet	47°10'	122°50'	1
2419.2	Budd Inlet	47°06.9'	122°54.8'	6
2419.3	Eld Inlet	47°07.6'	122°57'	2
2419.4	Totten Inlet	47°09.6'	122°59.3'	2
2420.1	Tala Point	47°56.2'	122°38.1'	113
2420.2	Hazel Point	47°41.9'	122°45.7'	4
2420.3	Dabob Bay	47°44.6'	122°50.2'	2
2421.1	Hood Point	47°37.7'	122°55.6'	4
2421.2	Tekiu Point	47°35.5'	122°58.5'	1
2421.3	Musqueti Point	47°23.1'	123°07.8'	4
2421.4	Union	47°21.4	123°08.4'	1
2421.5	Lynch Cove	47°24'	122°55.6'	2
2421.6	Lilliwaup River	47°27.3'	123°05.8'	1
2421.7	Hamma Hamma River	47°32.7'	123°01'	3
2430.1	Possession Point	47°54.2'	122°21.5'	3
2431.2	Camano Head	48°02.8'	122°22.2'	5
2431.4	Port Susan Bay	48°06.3'	122°22'	1
2432.1	Camano Village	48°11'	122°33.4'	5
2432.2	Watsak Point Buoy	48°14.1'	122°34.9'	1
2432.3	Skagit Flats	48°17'	122°30.3'	2
2432.5	Polnell Point	48°16.2'	122°32'	1
2433.1	Goat Island	48°21.7'	122°33.2'	1
2433.2	Hope Island	48°22.9'	122°34.4'	3
2433.3	Gibraltar	48°25'	122°35.9'	1

TABLE 10-10. Present Oceanographic Stations Repeatedly Visited in Puget Sound and Approaches. Stations Occupied at Approximately One Month Intervals Since 1952, Irregulary From 1948 to 1952.

STATION NUMBER	NAME (Nearest Landmark)	LATITUDE N.	LONGITUDE W.	FORMER STATION NUMBER
8182/4032	Pillar Point	48°18.2'	124°03.2'	2312.1
8178/3523	Otter Point	48°17.8'	123°52.3'	
8157/3412	Beechy Head	48°15.7'	123°41.2'	
8145/3323	Race Rocks	48°14.5'	123°32.3'	
8120/3235	Ediz Hook	48°12.0'	123°23.5'	
8150/3139	New Dungeness, NW of	48°15.0'	123°13.9'	
8156/3038	New Dungeness, NE of	48°15.6'	123°03.8'	
8124/2529	Protection Island	48°12.4'	122°52.9'	
8106/2466	Middle Point	48°10.6'	122°46.6'	
8082/2412	Port Townsend	48°08.2'	122°41.2'	2411.3
8056/2387	Marrowstone Point	48°05.6'	122°38.7'	
8017/2375	Bush Point	48°01.7'	122°37.5'	
7573/2345	Double Bluff	47°57.3'	122°34.5'	
7540/2286	Point No Point	47°54.0'	122°28.6'	2413.5
7490/2750	Applecove Point	47°49.0'	122°75.0'	
7444/2254	Point Jefferson	47°44.4'	122°25.4'	2414.2
7398/2280	West Point	47°39.8'	122°28.0'	2415.1
7342/2265	Alki Point	47°34.2'	122°26.5'	2415.2
7303/2251	Dolphin Point	47°30.3'	122°25.1'	
7265/2235	Pully Point	47°26.5'	122°23.5'	2416.1
7230/2212	Point Robinson	47°23.0'	122°21.2'	
7192/2280	Brown Point	47°19.2'	122°28.0'	2417.1
7190/2336	Pt. Defiance	47°19.0'	122°33.6'	
7167/2322	Point Evans	47°16.7'	122°32.2'	
7149/2344	Day Island	47°14.9'	122°34.4'	
7110/2380	Gordon Point	47°11.0'	122°38.0'	2417.4
7072/2424	Nisqually Reach	47°07.2'	122°42.4'	2417.5
7100/2473	Devils Head	47°10.0'	122°47.3'	2417.6
7170/2428	Green Point (Carr Inlet)	47°17.0'	122°42.8'	2417.3
7306/2291	Point Vashon	47°30.6'	122°29.1'	2415.5

TABLE 10-10. Present Oceanographic Stations Repeatedly Visited in Puget Sound and Approaches. Stations Occupied at Approximately One Month Intervals Since 1952, Irregularly From 1948 to 1952 (continued).

STATION NUMBER	NAME(Nearest Landmark)	LATITUDE N.	LONGITUDE W.	FORMER STATION NUMBER
7247/2317	Olalla	47°24.7'	122°31.7'	
7211/2324	Spring Beach	47°21.1'	122°32.4'	2416.3
7561/2380	Tala Point	47°56.1'	122°38.0'	2420.1
7500/2400	South Point	47°50.0'	122°40.0'	
7149/2457	Hazel Point	47°41.9'	122°45.7'	2420.2
7500/2487	Dabob Bay, Head	47°50.0'	122°48.7'	
7468/2485	Bolton Peninsula, East	47°46.8'	122°48.5'	
7448/2498	Tabook Point	47°44.8'	122°49.8'	2420.3
7418/2518	Tskutsko Point	47°41.8'	122°51.8'	
7401/2524	Pleasant Harbor	47°40.1'	122°52.4'	
7357/2580	Tekiu Point	47°35.7'	122°58.0'	2421.2
7286/3040	Eagle Creek	47°28.6'	123°04.0'	
7261/3064	Red Bluff, North of	47°26.1'	123°06.4'	
7233/3079	Musqueti Point	47°23.3'	123°07.9'	2421.3
7215/3038	Tahuya River	47°21.5'	123°03.8'	
7225/2597	Lynch Cove, Middle	47°22.5'	122°59.7'	
7239/2559	Lynch Cove	47°23.9'	122°55.9'	2421.5
7537/2212	Possession Point	47°53.7'	122°21.2'	2430.1
7585/2170	Port Gardener	47°58.5'	122°17.0'	
8029/2225	Camano Head, West	48°02.9'	122°22.5'	2431.2
8065/2295	East Point	48°06.5'	122°29.5'	
8110/2330	Onamac Point	48°11.0'	122°33.0'	2432.1
8140/2331	Demock Point	48°14.0'	122°33.1'	
8185/2295	Strawberry Point, North of	48°19.5'	122°29.5'	
8214/2334	Goat Island	48°21.4'	122°33.4'	2433.1
8249/2359	Dewey	48°24.9'	122°35.9'	2433.3
8265/2443	Lawson Reef, North of	48°26.5'	122°44.3'	
8040/2197	Camano Head, East of	48°04.0'	122°19.7'	
8062/2220	Port Susan, Middle	48°06.2'	122°22.0'	2431.4
8093/2243	Port Susan, Head	48°09.3'	122°24.3'	
8015/2318	Holmes Harbor, Head	48°01.5'	122°31.8'	
8031/2318	Classic	48°03.1'	122°31.8'	
8048/2322	Dines Point	48°04.8'	122°32.2'	
8062/2330	Greenbank	48°06.2'	122°33.0'	

Appendix 10-A

TIDE DESCRIPTION

The equilibrium tide--the standard reference for tides--would occur if the water was always in equilibrium with the tide-producing forces. While natural tides usually have much greater ranges than equilibrium tides, they exhibit approximately the same characteristic variations with the changing positions of sun and moon. Deviations from the standard reference are caused by large scale topographic features which influence the response of the ocean to the tide-producing forces.

The harmonic constants--the amplitude and epochs of the harmonic constituents of the tide--for each locality give a complete description of its tide, but are not convenient, as such, for use in comparing those of different localities since it is no easy matter to grasp the overall effect of the many possible different combinations of phases and amplitudes. In order to facilitate such a comparison use is made of certain characteristics of the tide enumerated in the following paragraphs.

1. Type of tide. Where the ratio $(K_1+O_1)/(M_2+S_2)$ is less than 0.25, the type is semidiurnal; where it is greater than 1.50, the type is diurnal; where it lies between these two values the type is mixed with the inequality principally in the high waters, low waters, or approximately the same in both, as the value of $M_2^\circ-K_1^\circ-O_1^\circ$ lies nearer 0°, 180°, or either 90° or 270°, respectively (Marmer 1951; Harris 1894).

2. Mean and diurnal ranges of tide.

3. Ratio of spring to neap range. Where the ratio S_2/M_2 is greater than 0.46, the ratio of spring to neap range is greater then that for the equilibrium tide; and where it is less than 0.46, the spring tides are relatively undeveloped. The approximate ratio of spring to neap tide is $\frac{1+S_2/M_2}{1-S_2/M_2}$, which is 2.7 for the equilibrium tide.

4. Ratio of perigean to apogean range. Where the ratio N_2/M_2 is greater than 0.19, the ratio of perigean to apogean range is greater than that for the equilibrium tide; and where it is less than 0.19, the perigean tides are relatively undeveloped. The approximate ratio of perigean to apogean tide is $\frac{1+N_2/M_2}{1-N_2/M_2}$ which is 1.5 for the equilibrium tide.

5. Ratio of tropic to mean diurnal inequality. Where the ratio O_1/K_1 is greater than 0.71, the ratio of tropic to mean diurnal inequality is greater than that for the equilibrium tide; and where it is less then 0.71,

the tropic tides are relatively undeveloped. The ratio of tropic to mean diurnal inequality is approximately $0.9(1+\frac{O_1}{K_1})$ which gives 1.5 for the equilibrium tide (Harris 1894).

6. Lunitidal interval, $\frac{M_2^{\circ}}{28.98}$. The lunitidal interval is the mean time lag of the tide at a station behind its equilibrium tide in hours.

7. Phase age, $\frac{S_2^{\circ}-M_2^{\circ}}{s_2-m_2}$. The phase age is the time lag of spring tides behind new and full moon, or of neap tides behind the moon's quadrature in hours.

8. Parallax age, $\frac{M_2^{\circ}-N_2^{\circ}}{m_2-n_2}$. The parallax age is the time lag of the greatest increase or decrease in tide range due to parallax behind moon in perigee or moon in apogee in hours, respectively.

9. Diurnal age, $\frac{K_1^{\circ}-O_1^{\circ}}{k_1-o_1}$. The diuranl age is the time lag of the greatest or least diurnal inequality in the tides behind the tropic or equatorial moon in hours, respectively.

NOMENCLATURE

Tides

Symbol	Definition
G	Greenwich epoch; G=K, for a long period constituent; G=K + west longitude of station for a diurnal constituent; G=K + 2 x west longitude of station, for a semidiurnal constituent
H	Amplitude of a tidal constituent
$G(M_2)$, $G(N_2)$, etc.	Greenwich epoch of the M_2 constituent, N_2 constituent, etc.
M_2, N_2, etc.	Amplitude of the M_2 constituent, N_2 constituent, etc.
M_2°, N_2°, etc.	Epoch of the M_2 constituent, N_2 constituent, etc.
K	Epoch, the lag of the phase of a tidal constituent behind the phase of the corresponding equilibrium constituent

For additional and further descriptions of symbols refer to Tide and Current Glossary (Schureman 1941).

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1935. The Carbonate System in Sea Water and Equilibria at 0°C. in Saturated Solutions of Some Sea Water Salts. Thesis, University of Washington, Seattle, Washington, 79 pages. (Data obtained on waters of Puget Sound and adjacent areas.)

Igelsrud, Iver, Rex J. Robinson, and Thomas G. Thompson
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International Hydrographic Bureau
1933. Tides--List of Harmonic Constants. Special Publication no. 26, Monaco. (Seattle, Yokeko Point, and Port Townsend stations are listed for Puget Sound.)

Jamieson, Ida M.
1930. The Determination of Aluminum and Iron in Sea Water. Thesis, University of Washington, Seattle, Washington, 10 pages. (Analyses from Friday Harbor which are considered in error due to methods of storage. Also typographical errors in paper.)

Jentoft, Ralph E., Jr.
1952. A Study of the Determination of Potassium as the Metaperiodate. Thesis, University of Washington, Seattle, Washington, 113 pages. (Contains results of analysis of sea water from Puget Sound, Strait of Juan de Fuca, and various localities in the Atlantic and Pacific Oceans. An intensive study.)

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1929. The Sea Water at the Puget Sound Biological Station from September 1927 to September 1928. Publications Puget Sound Biological Station, vol. 7, pp. 119-128.

Jorgenson, Wilhelm
1938. Spectral Transmission and Spectral Scattering of Daylight in the Sea. Thesis, University of Washington, Seattle, Washington, 53 pages.
(Description of equipment and data from several stations in oceanic waters off the coast of Washington and British Columbia and in the San Juan Archipelago.)

Jorgensen, Wilhelm with C. L. Utterback
1939. Periodic Changes in Spectral Scattering and Spectral Transmission of Daylight in Tidal Water. Sears Foundation: Journal of Marine Research, vol. 2, no. 1, pp. 30-37.
(Observations made during two month interval at one location in San Juan Archipelago.)

Knapman, Frederick W.
1941. The Sodium Content of Ocean Water. Thesis, University of Washington, Seattle, Washington, 21 pages.
(Data for stations in Puget Sound and adjacent areas.)

Lewis, George J., Jr.
1950. The Effect of Freezing on the Sulfate/Chlorinity Ratio in Sea Water. Thesis, University of Washington, Seattle, Washington, 19 pages.
(Sea water taken from Puget Sound.)

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(Sea water taken from Puget Sound.)

Lincoln, John H., Robert G. Paquette, and Marice Rattray, Jr.
1954. Microsalinometer for Oceanographic Model Studies. University of Washington, Department of Oceanography, Technical Report no. 26, 15 pages (mimeographed).
(Instrumentation on a small scale oceanographic model of Puget Sound including certain problems of salinity structure.)

Lucas, C. C.
1929. Further Oceanographic Studies of the Sea Adjacent to the Fraser River Mouth. Transactions of the Royal Society of Canada, 3d series, vol. 23, section 5, pp. 29-58, plus 10 plates.

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1927. A Bio-Hydrographical Investigation of the Sea Adjacent to the Fraser River Mouth. Transactions of the Royal Society of Canada, 3d series, vol. 21, section 5, pp. 485-520.

Marmer, H. A.
1932. Tides and Tidal Currents. Bulletin of the National Research Council, no. 85, Physics of the Earth-V, Oceanography, Chapter 7, pp. 229-309.
(Includes data for the Puget Sound area.)

1949. Sea Level Changes Along the Coasts of the United States in Recent Years. Transactions of the American Geophysical Union, vol. 30, no. 2, pp. 201-204.
(Seattle area included.)

1951. Tidal Datum Planes. U.S. Department of Commerce Coast and Geodetic Survey, Sepcial Publication no. 135 [Revised (1951) Edition], 142 pages.
(Illustrations include Seattle and the Puget Sound Area.)

1952. Changes in Sea Level Determined from Tide Observations. Proceedings of Second Conference on Coastal Engineering, Houston, Texas, November 1951, Edited by J. W. Johnson, The Engineering Foundation Council on Wave Research, pp. 62-67.
(Values for Seattle are given.)

McLellan, Peter M.
1954. An Area and Volume Study of Puget Sound, Washington. University of Washington, Department of Oceanography, Technical Report no. 21, 39 pages (mimeographed).

Nelson, Kurt H. and Thomas G. Thompson
1953. Desalting of Sea Water by Freezing Processes. University of Washington, Department of Oceanography, Technical Report no. 13, 22 pages (dittoed).
(The sea water used in the experiments was taken near the entrance to Puget Sound.)

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1951. Measurement of Tidal Currents in Puget Sound. University of Washington, Oceanographic Laboratories, Technical Report no. 6, 28 pages, plus tables and figures (dittoed).

Pearl, Irwin A. and H. K. Benson
1940. A Nitrosolignin Colorimetric Test for Sulfite Waste Liquor in Sea Water. Paper Trade Journal, vol. 111, no. 18, pp. 35-36. (Method of analysis with a few observations from the Puget Sound area.)

Phifer, Lyman D. and Thomas G. Thompson
1937. Seasonal Variations in the Surface Waters of San Juan Channel during the Five Year Period, January 1931 to December 30, 1935. The Sears Foundation: Journal of Marine Research, vol. 1, no. 1, pp. 34-59.

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1927. The Occurrence of Calcium and Magnesium Ions in the Waters of Puget Sound. Thesis, University of Washington, Seattle, Washington, 19 pages.

Poole, H. H. and W. R. G. Atkins
1930. Photo-electric Measurements of Submarine Illumination throughout the Year. Journal of the Marine Biological Association of the United Kingdom, vol. 16, new series, pp. 297-324. (Contains empirical relationship between extinction coefficients and Secchi Disc readings based on observations in English Channel. Of use in evaluating data only, no direct application to Puget Sound.)

Powers, Edwin B.
1920. The Variation of the Condition of Sea-water, Especially the Hydrogen-ion Concentration, and Its Relation to Marine Organisms. Publications Puget Sound Biological Station, vol. 2, no. 54, pp. 369-385.
(Puget Sound area.)

Raich, Abraham
1949. The Determination and Separation of Strontium from Calcium in Sea Water. Thesis, University of Washington, Seattle, Washington, 37 pages.
(Sea water obtained from the San Juan area.)

Rattray, Maurice, Jr.
1953. Tide and Current in Puget Sound. Corinthian Helmsman 1952, Published by the Corinthian Yacht Club, Seattle, Washington, pp. 47-55.
(Semi-technical for the lay reader.)

Redfield, Alfred C.
1950a. The Analysis of Tidal Phenomena in Narrow Embayments. Papers in Physical Oceanography and Meteorology, Massachusetts Institute of Technology and Woods Hole Oceanographic Institute, vol. 11, no. 4, pp. 1-36.
(Includes an analysis of the Juan de Fuca and Georgia Straits System.)

1950b. Note on the Circulation of a Deep Estuary--The Juan de Fuca--Georgia Straits. Proceedings of the Colloquium on the Flushing of Estuaries, Woods Hole Oceanographic Institute, Woods Hole, Mass., pp. 175-177.
(This system illustrates the saline counter current which appears to be a general feature of the circulation in estuaries and affords a good example of the use of temperature-salinity correlations in identifying the source of waters in an estuary.)

Robinson, Rex J.
1941. A Method of Freeing Sea Water of Phosphate. Science, vol. 93, no. 2405, pp. 117-118.
(Sea water from Friday Harbor.)

Robinson, Rex J. and Fred W. Knapman
1941. The Sodium-Chlorinity Ratio of Ocean Waters from the Northeast Pacific. The Sears Foundation: Journal of Marine Research, vol. 4, no. 2, pp. 142-152.
(Comparative data includes Puget Sound.)

Robinson, R. J. and T. G. Thompson
1940. Tidal Cycle Variations in the Composition of Sea Water. Association d'Oceanographie Physique, Union Geodesique et Geophysique Internationale, Proces-Verbaux, no. 3, p. 189.
(In or near the San Juan Islands area adjacent to Puget Sound.)

Robinson, Rex J. and Henry E. Wirth
1934a. Free Ammonia, Albuminoid Nitrogen, and Organic Nitrogen in the Waters of the Pacific Ocean off the Coasts of Washington and Vancouver Island. Journal du Conseil pour l'Exploration de la Mer, vol. 9, no. 2, pp. 187-195.
(Comparative data for Puget Sound included.)

1934b. Report on the Free Ammonia, Albuminoid Nitrogen and Organic Nitrogen in the Summers of 1931 and 1932. Journal du Conseil International pour l'Exploration de la Mer, vol. 9, no. 1, pp. 15-27.
(Includes data for Puget Sound.)

Robinson, Rex J. and Benjamin M. G. Zwicker
1941. Preparing Nitrate-Free Sea Water. Science, vol. 94, No. 2427, pp. 25-26.
(Sea Water from Friday Harbor.)

Ross, F. W. and C. L. Utterback
1939. Intensity Fluctuations in Components of Solar Radiation with Atmospheric Conditions. Journal du Conseil International pour l'Exploration de la Mer, vol. 14, no. 2, pp. 193-200.
(Observations at Friday Harbor, Washington.)

Schureman, Paul
1941. Tide and Current Glossary. U.S. Department of Commerce Coast and Geodetic Survey, Special Publication no. 228, Washirgton, D.C., 40 pages.
(Of use in tide and current analysis only, no direct implication to Puget Sound.)

Seckel, Gunter R.
1953. Salt Intrustion and Flushing of Lake Washington Ship Canal. Thesis, University of Washington, Seattle, Washington, 97 pages.

Seckel, Gunter R. and Maurice Rattray, Jr.
1953. Studies on Lake Washington Ship Canal. University of Washington, Department of Oceanography, Technical Report no. 15, 101 pages (mimeographed).
(Discussion of contamination of lake water by sea water and insight into the mechanism of two-layered flow and mixing.)

Selbo, Magnus L.
1940. Determination of Total Phosphorus in Sea Water. Thesis, University of Washington, Seattle, Washington, 13 pages.
(Puget Sound water evaluated.)

Shelford, V. E.
1929. The Penetration of Light into Puget Sound Waters as Measured with Gas Filled Photo-electric Cells and Ray Filters. Publications Puget Sound Biological Station, vol. 7, pp. 151-168.
(Observations at Friday Harbor, Washington.)

Shelford, Victor E. and Floyd W. Gail
1922. A Study of Light Penetration Into Sea Water Made with the Kunz Photo-Electric Cell With Particular Reference to the Distribution of Plants. Publications Puget Sound Biological Station, vol. 3, no. 65, pp. 141-176.
(Observations at Friday Harbor, Washington.)

Smith, E. Victor and Thomas G. Thompson
1925. The Control of Sea Water Flowing into the Lake Washington Ship Canal. Industrial and Engineering Chemistry, vol. 17, no. 10, pp. 1084-1087.
(A summary of results on a study of the invasion of salt water into Lake Union through the Locks of the Ship Canal. Pollution of the water for industrial use. A complete analysis.)

1927a. Occurrence of Hydrogen Sulfide in the Lake Washington Ship Canal. Industrial and Engineering Chemistry, vol. 19, no. 7, pp. 822-823.

1927b. Salinity of the Lake Washington Ship Canal. Bulletin University of Washington Engineering Experiment Station, no. 41, Seattle, Washington, 104 pages.
(A study of conditions affecting the flow of sea water into the canal system. A complete geographic analysis with plates, maps, and charts of the area outlining the entire problem.

Sverdrup, H. U., Martin W. Johnson, and Richard H. Fleming
1946. The Oceans. New York: Prentice-Hall, Inc., 1087 pages.
(Contains basic data and references.)

Taylor, Howard J.
1932. The Determination and Occurrence of Fluorine in Sea Water. Thesis, University of Washington, Seattle, Washington, 44 pages.
(Data from Strait of Juan de Fuca, San Juan area, and Pacific Ocean.)

Thomas, Bertram D.
1933. The Electrical Conductivity of Sea Water. Thesis, University of Washington, Seattle, Washington, 43 pages.
(Analyses include water from Puget Sound.)

Thomas, Bertram D., Thomas G. Thompson, and Clinton L. Utterback
1934. The Electrical Conductivity of Sea Water. Journal du Conseil International Pour l'Exploration de la Mer, vol. 9, no. 1, pp. 28-35.
(Analysis of waters of the Puget Sound Area included in the study.)

Thompson, Thomas G.
1930. A Progress Report on Ionic Ratios and Specific Gravity of Sea Water. Western Society of Naturalists, Contributions to Marine Biology, Stanford University Press, pp. 79-91.
(Concerns the water of Puget Sound.)

Thompson, Thomas G.
1935. The Oceanographic Laboratories of the University of Washington. The Collecting Net, vol. 10, no. 10, pp. 281-284. (Discussion of activities and research taking place.)

1937. The Oceanographic Laboratories of the University of Washington. The Biologist, vol. 18, no. 2, pp. 160-170. (Discussion of activities and research taking place.)

1940. Activities of the Oceanographic Laboratories of the University of Washington, Seattle, Washington. Proceedings of the Sixth Pacific Science Congress, Berkeley, Stanford and San Francisco, 1939, vol. 3, pp. 127-137. (Includes data and summary of work being undertaken in the Puget Sound Area.)

1952. Report on the Oceanographic Laboratories of the University of Washington. Proceedings of the Seventh Pacific Science Congress, Auckland and Christchurch, New Zealand, 1949, vol. 3, pp. 164-168. (Discussion on research being conducted in the Puget Sound area.)

Thompson, Thomas G. and Robert U. Bonnar
1931. The Buffer Capacity of Sea Water. Industrial and Engineering Chemistry, Analytical Edition, vol. 3, no. 4, pp. 393-395. (An analysis made in the waters of Puget Sound. Factors causing variations are discussed.)

Thompson, Thomas G. and Raymond W. Bremner
1935. The Occurrence of Iron in the Water of the North East Pacific Ocean. Journal du Conseil International Pour l'Exploration de la Mer, vol. 10, no. 1, pp. 39-47. (Includes analysis in the San Juan area.)

Thompson, Thomas G., Raymond W. Bremner, and I. Marion Jamieson
1932. Occurrence and Determination of Iron in Sea Water. Industrial and Engineering Chemistry, Analytical Edition, vol. 4, no. 3, pp. 288-290. (Analysis made in the Strait of Juan de Fuca and the San Juan Archipelago.)

Thompson, Thomas G., Dale C. Burtner, and Tsaihwa J. Chow
1954. Flame Photometric Determination of Strontium in Sea Water. Manuscript in Department of Oceanography, University of Washington, Seattle, Washington. (Unpublished.)

Thompson, T. G. and I. Igelsrud
1937. The Solubility of Boron in the Waters of the North Pacific. Association d'Oceanographie Physique, Union Geodesique et Geophysique Internationale, Proces-Verbaux no. 2, p. 155. (Includes values for Puget Sound.)

Thompson, T. G. and Martin W. Johnson
1930. The Sea Water at the Puget Sound Biological Station from September 1928 to September 1929. Publications Puget Sound Biological Station, vol. 7, pp. 345-368.

Thompson, Thomas G., Martin W. Johnson, and Seldon P. Todd
1928. The Sea Water at the Puget Sound Biological Station from September 1926, to September 1927. Publications Puget Sound Biological Station, vol. 6, pp. 371-394.

Thompson, Thomas G. and Edwin Korpi
1942. The Bromine-Chlorinity Ratio of Sea Water. The Sears Foundation: Journal of Marine Research, vol. 5, no. 1, pp. 28-36. (Includes comparative data for Puget Sound.)

Thompson, Thomas G., Joseph W. Lang, and Lucile Anderson
1927. The Sulphate-Chlorinity Ratio of the Waters of the North Pacific. Publications Puget Sound Biological Station, vol. 5, pp. 277-292. (Puget Sound and San Juan areas included.)

Thompson, Thomas G., Roberta McCorkell, and Robert U. Bonnar
1930. A Summary of the Studies of the Phosphate Content of the Waters of the San Juan Archipelago. Western Society of Naturalists, Contributions to Marine Biology, Stanford University Press, pp. 82-86.

Thompson, Thomas G. and Robert C. Miller
1928. Differences Observed in the Condition of the Sea Water at the Margins of Two Opposing Tidal Currents. Science, vol. 68, no. 1769, pp. 517-518.
(Observations made in the waters just north of San Juan Island. Reference is made to the intensity of noise at the interface of the tide rip, which may be of significance due to its magnitude.)

Thompson, Thomas G., Robert C. Miller, George H. Hitchings, and Seldon P. Todd
1929. Studies of the Sea Water Near the Puget Sound Biological Station During the Summer of 1927. Publications Puget Sound Biological Station, vol. 7, pp. 65-99.

Thompson, Thomas G. and Lyman D. Phifer
1936. The Plankton and the Properties of the Surface Waters of the Puget Sound Region. University of Washington Publications in Oceanography, vol. 1, no. 5, pp. 111-134.

Thompson, Thomas G. and Rex J. Robinson
1932. Chemistry of the Sea. Bulletin of the National Research Council, no. 85, Physics of the Earth-V, Oceanography, Chapter 5, pp. 95-203.
(Includes data for the Puget Sound area.)

1934. The Sea Water of the Puget Sound Region. Proceedings of the Fifth Pacific Science Congress, Victoria and Vancouver, B.C., Canada, 1933, vol. 3, pp. 2101-2107.

Thompson, Thomas G. and Howard Jean Taylor
1933. Determination and Occurrence of Fluorides in Sea Water. Industrial and Engineering Chemistry, Analytical Edition, vol. 5, no. 2, pp. 87-89.
(Analysis made in the Strait of Juan de Fuca and the San Juan Islands.)

Thompson, Thomas G. and Thomas L. Wilson
1935. The Occurrence and Determination of Manganese in Sea Water. Journal of the American Chemical Society, vol. 57, no. 2, pp. 233-236
(Analysis of the waters of Puget Sound. Includes analysis of Plankton, muds, and other bottom deposits.)

Thompson, Thomas G. and Calvert C. Wright
1930. Ionic Ratios of the Waters of the North Pacific Ocean. Journal of the American Chemical Society, vol. 52, no. 3, pp. 915-921.
(Includes analysis of samples from the San Juan area.)

Tilley, John N. and Balwen A. Semb
1928. A Study of the Waters of the Lake Washington Ship Canal. Thesis, University of Washington, Seattle, Washington, 66 pages.
(Detailed chemical analysis.)

Todd, Seldon P.
1928. The Sea Water at the Puget Sound Biological Station. Thesis, University of Washington, Seattle, Washington, 28 pages.
(Concerns the San Juan area in which the station was located.)

Trumble, Robert E., Jr.
1947. Reflection of Visible Solar Radiation at the Surface of Inshore Ocean Waters. Thesis, University of Washington, Seattle, Washington, 42 pages.
(Measurements made at Friday Harbor, Washington.)

Tully, John P.
1942. Surface Non-Tidal Currents in the Approaches to Juan de Fuca Strait. Journal of the Fisheries Research Board of Canada, vol. 5, no. 4, pp. 398-409.
(It is shown that the system represents a balance between a wake stream flow from Juan de Fuca Strait, which is directly related to the volume of land drainage, and the independent wind-driven currents, which are due to one of the two prevailing coastwise winds in the area.)

University of Washington Department of Meteorology
n.d. Wind data obtained from University facilities. On file in the Department of Meteorology, Seattle. (Unpublished.)

University of Washington Department of Oceanography
1952. Preliminary Oceanography Survey on Submarine Portion of Snohomish-Kitsap 230KV Line. Progress Report no. 1, Submitted to Bonneville Power Administration, 7 pages (dittoed).
(Contains resumé of oceanographic factors and analysis of available temperature and salinity data; currents; and bottom characteristics.)

1953. Oceanographic Survey on Submarine Portion of Snohomish-Kitsap 230KV Line. Final Report--Part I, Submitted to Bonneville Power Administration, 173 pages (dittoed).
(Physical oceanography studies include work on the distribution of temperature, salinity, density, pressure, currents, tides, and surface wind waves of Puget Sound.)

1954a. Oceanographic Research Periodic Status Report for Work Performed Under Contract No. N8onr-520/III, Project No. NR 083 012, of the Office of Naval Research. No. 21 for the period 1 January-31 March 1954, no. 17 for the period 1 July-31 December 1952.
(Summarizes work performed within the various phases of oceanography studied.)

1954b. Periodic Status Report for Work Performed Under Contract No. Nonr-477(01), Project No. NR 084 011, for the Office of Naval Research. No. 9 for the period 1 January-31 March 1954, no. 4 for the period 1 June-30 September 1952.
(Summarizes work and operations performed aboard the M. V. BROWN BEAR, research vessel operated by the University.)

University of Washington Oceanographic Laboratories

1952a. Oceanographic Research Periodic Status Report for Work Performed under Contract No. N8onr-520/III, Project No. NR 083 012, of the Office of Naval Research. No. 16 for the period 1 April-30 June 1952, no. 1 for the period 15 March-30 September 1948.

1952b. Periodic Status Report for Work Performed Under Contract No. Nonr-477(01), Project No. NR 084 011, of the Office of Naval Research. No. 3 for the period 1 January-31 May 1952, no. 1 for the period 1 June-30 September 1951.

U.S. Army Corps of Engineers

1952. Personal communication on the effect of ships' wakes on shore installations in Puget Sound. Letter from K. F. Smrha, Chief, Operations Division, to Peter McLellan, dated 26 June 1952. (No study has been made by the Corps of Engineers. With the exception of speed regulations for the Lake Washington Ship Canal, no regulations have been prescribed for this area at reducing the damage caused by ships' wakes.)

U.S. Department of Commerce Coast and Geodetic Survey

n.d. Tidal Bench Mark Data. Washington, D.C. (Published on separate sheets by index map number and the name of the locality in which located. Each sheet is individually issued and dated.)

1923-27. 1949-51. Current tables, Pacific coast North America for the year____.

1928-48. Current tables, Pacific coast North America and Philippine Islands for the year____.

1952-53. Current tables, Pacific coast North America and Asia for the year____. Government Printing Office.

1867-85. Tide tables for the Pacific coast of the United States for the year____.

1886-89. Tide tables for the Pacific coast of the United States together with a few stations in Lower California, British Columbia and Alaska Territory for the year____.

1890-91. Tide tables for the Pacific coast of the United States together with 121 stations in Lower California, British Columbia and Alaska Territory for the year____.

U.S. Department of Commerce Coast and Geodetic Survey

1892. Tide tables for the Pacific coast of the United States together with 132 stations in Lower California, British Columbia and Alaska Territory for the year____.

1893-94. Tide tables for the Pacific coast of the United States together with 150 stations in Lower California, British Columbia and Alaska Territory for the year____.

1895. Tide tables for the Pacific coast of America together with stations in Asia, Australia and islands of the Pacific Ocean for the year____.

1896-1900. Tide tables for the Pacific coast of the United States (reprinted from Tide Tables for ____).

1901. Tide tables for the Pacific coast of the United States, including British Columbia and Alaska (reprinted from Tide Tables for ____).

1902-14. Tide tables for the Pacific coast of the United States, together with a number of foreign ports in the Pacific Ocean (reprint from Tide Tables for ____).

1915-21. Pacific coast tide tables for Western North America, Eastern Asia and many island groups for the year____ (reprinted from the General tide tables).

1922. Tide tables, Pacific coast North America, Eastern Asia and island groups including data on currents for the year____ (reprinted from the Tide Tables, United States and foreign ports).

1923-33. Tide tables, Pacific coast North America, Eastern Asia and island groups for the year____ (reprinted from the Tide Tables, United States and foreign ports).

1934-50. Tide tables, Pacific Ocean and Indian Ocean for the year____.

1949-53. Tide tables, west coast North and South American, (including the Hawaiian Islands) for the year____. Government Printing Office.

1938. Tidal Bench Marks, State of Washington, Washington, D.C., 109 pages.
(Description and locations of all bench marks, federal, state, and municipal (a collection of single sheets bound).)

U.S. Department of Commerce Coast and Geodetic Survey

1941a. Density of Sea Water, Coast and Geodetic Survey Tide Stations, Pacific Coast. Publication DW-2, 44 pages. (Includes Puget Sound area.)

1941b. Water Temperatures, Coast and Geodetic Survey Tide Stations, Pacific Coast. TW-2, 46 pages. (Includes Puget Sound Stations.)

1942. Tidal Harmonic Constants--Pacific and Indian Oceans. Publication TH-2, Washington, 133 pages. (Contains tidal constants for nine locations in the Puget Sound area.)

1946. Index Map, Tidal Bench Marks, Washington. Washington, D.C. (Lists tidal bench marks by numbered positions.)

1948. Tidal Current Charts, Puget Sound, Southern Part. Serial 713, Government Printing Office, Washington.

1949. Surface Water Temperatures at Coast and Geodetic Survey Tide Stations, Pacific Ocean. Publication TW-2, Revised (1948) Edition, 47 pages. (Contains data for Puget Sound.)

1952a. Density of Sea Water at Coast and Geodetic Survey Tide Stations, Pacific Ocean. Publication DW-2, Revised (1950) Edition, 37 pages. (Stations in Puget Sound including Mean Salinity Curves.)

1952b. Personal communication on Tidal Harmonic Constants for the Puget Sound Area. Letter from Robert W. Knox, Acting Director, to Peter McLellan, dated December 16, 1952. (The only additional station to those in publication TH-2 in the Puget Sound area for which harmonic constants are available is Everett.)

1952c. Personal communication on the tide survey program now in effect in Puget Sound. Letter from Robert W. Knox, Acting Director, to Peter M. McLellan, dated July 2, 1952.

1952d. Surface Water Temperatures at Tide Stations, Pacific Coast, North and South America and Pacific Ocean Islands. Special Publication no. 280, 59 pages. (Contains data for Puget Sound.)

1952e. Tidal Current Charts, Puget Sound, Northern Part. Serial no. 696, Government Printing Office, Washington.

U.S. Department of Commerce Coast and Geodetic Survey
1953a. Communication on reliability of measurements in Puget Sound. Note from Captain Charles Pierce, Supervisor N.W. District, to Department of Oceanography, (April 6, 1953).

1953b. Personal communication on present tidal current surveys in Puget Sound. Letter from Robert W. Knox, Acting Director, to Peter McLellan, dated 10 April 1953.

U.S. Navy Hydrographic Office
1951. Techniques for Forecasting Wind Waves and Swell. H.O. Publication, no. 604, Hydrographic Office, Washington, D.C., 37 pages. (Techniques may be applied to Puget Sound.)

Utterback, C. L.
1933. Variations in Visible Solar Light During Submarine Measurements. Science, vol. 77, no. 1987, pp. 118-119.

1935. Submarine Illumination. Transactions of the American Geophysical Union, Sixteenth Annual Meeting, pp. 250-256. (Includes some data for the San Juan and Juan de Fuca Straits areas.)

Utterback, C. L. and J. Watson Boyle
1933. Light Penetration in the Waters of the San Juan Archipelago. The Journal of the Optical Society of America, vol. 23, no. 10, pp. 333-338. (Limited amount of data.)

Utterback, C. L. and Wilhelm Jorgensen
1934. Absorption of Daylight in the North Pacific Ocean. Journal du Conseil International pour l'Exploration de la Mer, vol. 9, no. 2, pp. 197-209. (Area adjacent to Puget Sound discussed.)

1936. Scattering of Daylight in the Sea. The Journal of the Optical Society of America, vol. 26, pp. 257-259.

Utterback, C. L. and Eugene K. Miller
1937. Variations in Components of Submarine Daylight for 1933 and 1936. Journal du Conseil International pour l'Exploration de la Mer, vol. 12, no. 3, pp. 305-310. (Observations at roughly monthly intervals at Pillar Point and Point No Point.)

Utterback, C. L., Thomas G. Thompson, and Bertram D. Thomas
1934. Refractivity-Chlorinity-Temperature Relationships of Ocean Waters. Journal du Conseil International Pour l'Exploration de la Mer, vol. 9, no. 1, pp. 35-38.
(Analysis of the waters of Puget Sound included in the study.)

Utterback, C. L. and Raymond E. Wilson
1940. Submarine Illumination in Photometric Units. The Journal of the Optical Society of America, vol. 30, no. 3, pp. 136-139.
(Data for several stations reported in illumination units.)

Utterback, C. L. and L. A. Sanderman
1948. Radium Analyses of Marine Sediments in Northern Pacific and Adjacent Waters. The Sears Foundation: Journal of Marine Research, vol. 7, no. 3, pp. 634-643.
(Includes discussion of data from Skagit Bay, Hood Canal, and East Sound.)

Waldichuk, Michael
1952. Oceanography of the Strait of Georgia--I. Salinity Distribution. Fisheries Research Board of Canada, Progress Reports of the Pacific Coast Stations, no. 93, pp. 26-29.

1953a. Oceanography of the Strait of Georgia--II. Temperature Distribution. Fisheries Research Board of Canada, Progress Reports of the Pacific Coast Stations, no. 94, pp. 19-23.

1953b. Oceanography of the Strait of Georgia--III. Character of the Bottom. Fisheries Research Board of Canada, Progress Reports of the Pacific Coast Stations, no. 95, pp. 59-63.

1953c. Oceanography of the Strait of Georgia--IV. Dissolved Oxygen Distribution. Fisheries Research Board of Canada, Progress Reports of the Pacific Coast Stations, no. 96, pp. 6-10.

1954. Chemistry of Puget Sound Waters and Influencing Factors. Manuscript in Department of Oceanography, University of Washington, Seattle, Washington. (Unpublished.)
(Discusses chemical constituents from standpoint of sources and circulation.)

Waldie, R. J.
1950. Fresh Water in Georgia Strait. Fisheries Research Board of Canada, Progress Reports of the Pacific Coast Stations, no. 83, pp. 42-44.
(Percentage and distribution of fresh water from the Fraser River observed in May 1950. Strait of Juan de Fuca and San Juan Islands area included.)

West, Lloyd E.
1939. Potentiometric Determinations of the Chlorinity, Magnesium, and Alkalinity of Sea Water. Thesis, University of Washington, Seattle, Washington, 82 pages.
(Water from the Strait of Juan de Fuca analyzed.)

Williams, Emile A.
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SECTION 11: MARINE BIOLOGY

25 March 1953

MARINE BIOLOGY

FISHERIES BIOLOGY

COMMERCIAL FISHERIES

To a considerable degree the waters of Puget Sound contribute much less to the overall regional fishery than do the waters which are immediately adjacent. Some species of both fish and shellfish, however, do occur in quantity and are of commercial importance. Appendix 11-A shows the principal fishing areas within Puget Sound and the major fish and shellfish which are taken in each area. Appendix 11-B contains a summary of the personnel and equipment which were employed in the Puget Sound area in 1949.

Local Methods of Commercial Fishing

Various methods of commercial fishing have been adopted in the local fishery; following is a brief description of the major types.

TROLLERS. The trolling boat usually consists of a medium sized motor launch with several long extended poles. From each of these poles run long fishing lines to which one or more lures are attached. As the fish strike these lines they are towed behind the boat and landed individually. The chinook and silver salmon for the most part are caught in this manner.

PURSE SEINES. The purse seine is operated from a considerably larger boat than the troller and consists of a large net floated by corks along one edge and weighted along an opposite edge so as to hang vertically in the water. The object is to encircle a school of fish, close the net around them in the form of a "purse" and then draw the net aboard the vessel. All the species of salmon as well as smelt and flounder are taken in this manner.

GILL NETS. Gill nets, which are usually operated from small boats, are floated vertically in the water in the same manner as the purse seine. They are laid out in a straight line across the area to be fished and the fish become entangled in the web of the net as they attempt to pass through. All species of salmon as well as flounder, ling cod and steelhead are taken in this manner.

REEF NETS. Reef nets are suspended horizontally in the water and are operated between two boats, usually near a reef or in an area where fish must pass. When fish are sighted passing over the net it is raised and the fish are captured. This method is commonly used by the local Indians as well as commercial fisherman but only in the northern parts of Puget Sound (Washington State Department of Fisheries 1951b). The salmon are the only fish taken in this manner.

OTTER TRAWLS. The otter trawl consists of a large webbed net shaped like a closed sack and is towed behind a slowly moving boat. On either side of the trawl, vanes are rigged so as to hold open the mouth of the net as it passes through the water. Herring, perch, ling cod, rat-fish, skates, dog-fish, squid, octopus and sole are taken in this manner.

OTHER METHODS. Other methods of commercial fishing which are used locally include the use of drag seines, beam trawls, brush weirs, set nets, set lines, and various forms of Indian traps.

Catch Statistics

In Table 11-1 are shown the numbers of each of the five species of Pacific Salmon which were taken on Puget Sound in 1951. Individual catch statistics for all major commercial fish taken on Puget Sound are available at Washington State Department of Fisheries, Research Division.

Location and Concentration of Fishing Vessels

Concentrations of commercial fishing vessels in various localities are subject to the migration periods of the fish and prevailing regulations governing commercial fishing. During the open season the entrance to Hood Canal, Port Susan, and Everett Harbor are at times almost completely blocked by the fishing boats and gear. The Notice to Mariners, 13th Coast Guard District, occasionally carries a reference to this congestion. In addition to the commercial fishing vessels, sports fishermen in small craft can be expected at almost any time and place, and at times are also concentrated in great numbers. Appendixes 11-A and 11-B summarize the principal fishing areas and operating units in Puget Sound.

For information concerning commercial and sport fishing laws in Puget Sound, reference is made to Orders of the Director of Fisheries (Anderson 1950), and Pacific Northwest Food Fishes (Washington State Department of Fisheries 1951b).

TABLE 11-1. Catch of Salmon Within Puget Sound, 1951.*
[In numbers of fish]

SPECIES	TAKEN IN SALT WATER	TAKEN IN FRESH WATER (1)	TOTAL
Chinook	19,586	1,799	21,385 (2)
Pink	579,845	2,033	581,878 (3)
Chum	561,495	59,823	621,318 (4)
Sockeye	28,294	1	28,295 (5)
Silver	141,640	7,205	148,845 (6)
Totals	1,330,860	70,861	1,401,721

* Does not include any area north or west of West Beach (Whidbey Island).

(1) Except for the Skagit River, these numbers constitute fish taken by Indians in the rivers.

(2) Includes 16,074 fish taken in Skagit Bay.

(3) Includes 409,066 fish taken in Port Susan and Port Gardner.

(4) Includes 199,677 fish taken in Admiralty Inlet and 129,530 fish taken in Skagit Bay.

(5) Includes 763 fish taken in Skagit Bay.

(6) Includes 52,587 fish taken in Port Gardner and Port Susan and 30,432 fish taken in Skagit Bay.

Table summarized from Puget Sound Salmon, 1949 and 1951 (Washington State Department of Fisheries n.d.c).

The Pacific Salmon

The most highly valued fish to be found in Puget Sound and its adjacent waters are the five species of Pacific salmon; the chinook, silver, sockeye, pink, and the chum. Since all are extremely migratory, they are most abundant during the periods when they travel to their spawning grounds in the freshwater rivers and streams. All are monoreproducing and no instance is on record where a Pacific salmon has made a second spawning migration.

CHARACTERISTICS, HABITS, AND SPECIES. The chinook or king salmon Oncorhynchus tshawytscha usually enter freshwater sometime in the summer or fall and spawn from about the middle of August through October. Upon hatching, the young may remain in the streams till the second year or leave for the ocean where they will mature in from two to four years. At maturity their average weight is about 22 pounds, however, 40 to 60 pound chinook are not rare.

The habits of the silver or cohoe salmon O. kisutch are similar to those of the chinook; however, their time of migration is somewhat later. Usually they enter the streams in October and November and hatch about February. The young hatched silvers usually remain in the streams a year, then spend another year and a few months in the ocean before returning in the fall. Thus, while maturing and spawning, they are usually three years old. The average weight of a mature silver is about 10 pounds.

The pink or humpback salmon O. gorbuscha has a spawning migration period in late summer or early fall and the young fish immediately travel downstream to mature in two years. It has been characteristic of these fish locally to have "runs" only in the odd numbered years. The pink salmon averages about 5 1/2 pounds at maturity and rarely exceeds 10 pounds.

For the most part the spawning migration of the sockeye salmon O. nerka takes place in the summer and only one small run takes place in Puget Sound. This is the group of fish going the Skagit and Baker Rivers. The habits of these fish much resemble the chinook except for one characteristic that distinguishes them from the others. That is that they will only spawn in the rivers where there is a lake they can reach. Usually they mature at four and five years at which time they weigh from 5 to 7 pounds.

The chum or dog salmon O. keta has a spawning migration in the late fall and like the pink salmon the young immediately leave for salt water where they mature at three and five years. Their average weight is about 10 pounds at maturity (Washington State Department of Fisheries 1951b; Clemens and Wilby 1949).

Oysters

SPECIES. Three species of oysters are common in the Puget Sound area; the Pacific oyster *Ostrea gigas* which was introduced from Japan in 1902, the native or Olympia oyster *O. lurida*, and the European flat oyster *O. edulis*. The Olympia and Pacific are the principal species.

REPRODUCTION. Despite a huge reproductive potential, oyster spawn has a relatively low survival rate. On an average of 2 years out of 5, natural spawning accounts for only about one-half of the optimum commercial reseeding; consequently the local oyster industry is dependent upon seed import from Japan to meet the market demand. The spawning period for local oysters is in the summer months.

SIZE. The Pacifics may reach 4 inches in shell size at 2 years, whereas the slower growing Olympia is only 1 1/2 inches long when it reaches maturity at 4 years.

OCCURRENCE. The principal oyster beaches occur in the bays of southern Puget Sound and the Hood Canal area (Washington State Department of Fisheries 1952e).

Clams

SPECIES. Principal species of hardshell clams to be found locally are the little neck or rock clam *Venerupis staminea*, the butter clam *Saxidomus giganteus*, the horse clam *Schizothaerus nuttalli* and the impressive goeduck clam *Panope generosa*.

REPRODUCTION. The reproductive and growth characteristics of the hardshell clams are similar to those of the oyster and reproduction takes place intermittently in the spring and summer months.

SIZE AND OCCURRENCE. Little necks concentrate in the tidal zone between minus 3 and plus 4 feet and within 6 inches of the surface. They usually do not exceed 2 1/2 inches in shell size.

Butter clams are most often found below the 2 foot tidal mark. Their adult size is about 3 to 5 inches.

The horse clam is found much deeper than the butter and little neck clam; usually from 1 to 3 feet below the surface and in the minus tide zone.

The Goeduck most often inhabits the sandy bars in the minus-tide zone. Some specimens have been dredged from water as deep as 30 fathoms. They are the largest of the local clams and often weigh as much as 20 pounds. The average weight is about 3 pounds (Washington State Department of Fisheries 1952e).

Crabs

SPECIES. The principal species of crab to be taken locally is the Dungeness crab *Cancer magister*.

REPRODUCTION AND SIZE. Mating usually occurs in May or June and hatching takes place in the following winter or early spring; the young crabs will first appear in adult form about 12 months after the mating--usually in June. At two years most of the crabs have reached maturity and measure about 4 inches in width. At 3 years the males measure about 5 3/4 inches in width-- the females are usually an inch less.

OCCURRENCE. The most productive grounds occur outside Puget Sound proper particularly in the Point Roberts area, Discovery Bay, Dungeness, and on the outer coast. Within the area they are principally found in Port Gardner, Port Susan, and Skagit Bay (Washington State Department of Fisheries 1952e).

FISH AND SHELLFISH KILLS

There are many instances where both fish and shellfish kills have been reported from various Puget Sound areas. Usually the responsible factors which cause them remain unknown, however, in some cases there is almost direct evidence for their occurrence. Highly suspected as a direct source are several local industries which spill, as a means of disposal, organic waste liquors into the Sound (Smoker, et.al. 1952). See section on Geography: Water Polution, for discussion on sources of pollution.

Port Gardner Bay

Extensive fish kills have been reported from time to time in this area. These kills have involved mostly herring, hake, smelt, candlefish and salmonoid scrapfish. Water analyses taken at the time of the kills have indicated the presence of sulphite waste liquors or in some instances unsatisfactory oxygen conditions (Orlob, Anderson, and Hansen 1949).

Mud Bay Area (Eld Inlet)

Although fish and shellfish kills in other regions have been attributed to red tide organisms, it appears probable but not certain that they may be the responsible factors in Puget Sound. In July 1951, a very heavy fish and shellfish mortality was reported from Mud Bay (Eld Inlet area) at which time a heavy rust colored plankton bloom also occurred. The pigmented plankton was subsequently identified as the red tide organism, *Gymnodinium splendens* (Washington State Department of Fisheries 1952c).

Des Moines-Redondo Area

From 13 September to 19 September 1952, an estimated 3000 silver salmon were killed in this area. Although lignins were found in the area, it is not believed that the kill was due to the normal course of domestic or commercial pollution but to some unusual or accidental event.

BIOLOGY

MARINE BORERS

Two organisms which are important contributors to marine boring in Puget Sound are the "shipworm," commonly known as the "teredo" and the "wood gribble." The following is a general description of their local activity.

The Shipworm

According to Johnson and Miller (Johnson and Miller 1935) the wood boring mollusks of the family Teredinidae are chiefly represented in the Puget Sound area by the large and destructive Shipworm Bankia setacea (Tryon) sp. In one isolated case, however, Teredo (Lyrodus) sp. has also been reported (Clapp 1950) and others possibly exist.

PERIOD OF SETTLEMENT. The settlement of Bankia setacea in some Puget Sound areas is reported to take place throughout the entire year (Martin 1938) while in other areas the periods of settlement are seasonal (Hower 1938). This is in accord with the following statement by Johnson and Miller in 1935:

> It may be concluded therefore that the principal season of settlement of Bankia setacea at Friday Harbor, and presumably in adjacent areas with comparable physical conditions, is in the months of October, November, and December; that settlement nearly or entirely ceases in January and February, begins again in March or April. goes on more or less sporadically through the summer, and increases suddenly in October to the fall maximum.

and:

> While it would be hazardous to assert that no settlement of larvae will occur outside this temperature range, (7°C to 12°C) the hypothesis is here suggested that these figures represent the limits of effective breeding of Bankia in Puget Sound, and that as long as the temperature of the water is above or below these limits no attack of destructive intensity is to be expected.
>
> (Johnson and Miller 1935.)

DEGREE AND LEVEL OF ATTACK. Table 11-2 shows the degree of Teredinidae attack on a yearly basis at thirteen Puget Sound locations. Figure 11-1 and Table 11-3 show the seasonal settlements of Bankia setacea at Shelton and

Friday Harbor, Washington. Location of all stations can be found in Fig. 1-2, section on Geography. Generally, the Teredinidae activity reported is most severe at more isolated stations. Where anomalous water conditions may prevail, the activity appears somewhat sporadic.

In consideration of the level at which Teredinidae attack is most intense, Johnson and Miller have found that Bankia setacea has a maximum activity near the mud line (Johnson and Miller 1935). This is shown in Table 11-3.

The Gribble or Sea Louse

Usually found with the Teredinidae are the small and abundant Isopod borers. In Puget Sound these organisms are mainly represented by Limnoria lignorum (Rathke).

PERIOD OF SETTLEMENT. Concerning the seasonal settlement of Limnoria, reference is made to a summary of the work of Johnson and Miller at Friday Harbor, Washington in 1935:

> Limnoria settled on the blocks in greatest abundance during the three month period starting March 1, with the maximum occurrence in April and May. After June 1, there was a rather sharp decline in numbers of Limnoria and through the remainder of the year the settlement was comparatively light.
>
> (Johnson and Miller 1935.)

The work of Hower at Shelton, Washington and Martin at Bremerton indicates, however, that the periods of settlement of these organisms varies with area in which they occur. The maximum breeding and migratory activity occurs between 7.5° and 9.7° C. (Johnson and Miller 1935).

DEGREE AND LEVEL OF ATTACK. The findings of both Hower and Martin indicate a maximum vertical activity near the mud line and zero low-tide datum (Hower 1938; Martin 1938). This agrees with Johnson and Miller's findings at Friday Harbor (Johnson and Miller 1935) and is a significant feature of these organisms as well as for the Teredinidae. All sources of information indicate that the vertical zone near the zero low-tide datum is most preferable for boring organisms and their activity diminishes in the higher tidal levels.

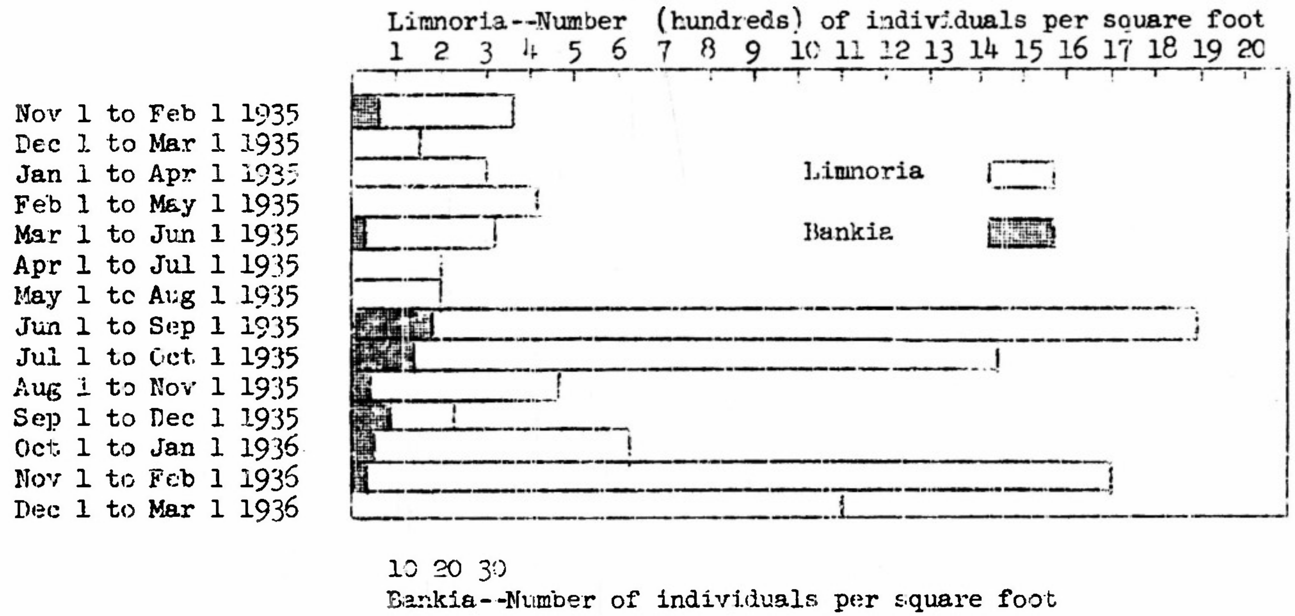

Fig. 11-1. The Seasonal Settlement of <u>Bankia setacea</u> and <u>Limnoria lignorum</u> at Shelton, Washington from November 1, 1935 to March 1, 1936. Data from (Hower 1938).

TABLE 11-2. Relative Degrees of Teredinidae Attack at Thirteen Puget Sound Locations.

LOCATION AND AGENCY	STATION NUMBER	1944	1945	1946	1947	1948	1949	1950	1951
Bellingham, U.S. Coast Guard	O-WASH-9					VH	VH	VH	VH
Friday Harbor, U.S. Coast Guard	O-WASH-5					VH	VH	VH	VH
Port Townsend, U.S. Coast Guard Moorings	O-WASH-10					VH	VH	VH	VH
Indian Island, U.S. Naval Magazine and Net Depot	USNII-1	VH	VH	MH	MH	H	H	H	H
Everett, U.S. Coast Guard Moorings	O-WASH-11					T	T	M	H
Bremerton, Puget Sound Naval Shipyard (Receiving Station Pier)	USNPS-1	VH	VH	VH	S	T	T	S	S
Bremerton, Puget Sound Naval Shipyard (Pier No.I)	USNPS-2	VH	VH	VH	S	MH	MH	MH	H
Bremerton, Puget Sound Naval Shipyard (Pier No.8)	USNPS-3	VH	VH	VH	S	M	M	M	H
Seattle, U.S. Naval Station (Pier 90)	USNS-1	VH	VH	VH	VH	VH	VH	VH	VH
Seattle, U.S. Naval Station (Pier 91)	USNS-2	VH	VH	VH	VH	VH	VH	VH	VH
Seattle, West Seattle (U.S. Coast Guard Moorings)	O-WASH-2							VH	VH
Tacoma, U.S. Naval Station	O-WASH-15					VH	VH	VH	VH
Olympia, U.S. Maritime Commission's Olympia Reserve Fleet, Budd Inlet	O-WASH-1					VH	M	VH	VH

Key

T - Trace	- 0 to 5 organisms
S - Slight	- 6-25 organisms
M - Moderate	- 26-100 or 25% filled
MH - Medium Heavy	- 101-250 of 50% filled
H - Heavy	- Over 250 or 75% filled
VH - Very Heavy	- Riddled or destroyed

Note: Method of measuring Teredinidae attack by standard test panels described in Report on Marine Borers and Fouling Organisms (U.S. Navy Bureau of Yards and Docks 1951).

Table modified from Clapp (Clapp 1952).

TABLE 11-3. Seasonal Settlement of <u>Bankia setacea</u> and <u>Limnoria lignorum</u> at Friday Harbor, Washington from October 1, 1928 to January 1, 1930. [Individuals per square foot.]

BLOCK \ DATE		Oct 1 to Jan 1	Nov 1 to Feb 1	Dec 1 to Mar 1	Jan 1 to Mar 28	Feb 1 to May 1	Mar 1 to Jun 1	Apr 1 to Jul 2	May 1 to Aug 2	Jun 1 to Sep 4	Jul 2 to Sep 26	Aug 2 to Oct 25	Sep 4 to Nov 29	Sep 26 to Jan 1
Bankia setacea	A													
	B													
	C	4	1	3								1	1	
	D	18	0^a	11		1^b			1^c		1^d	11	7	4
Limnoria lignorum	A					1								1
	B	35	28	18	350	150	214	1800	170	5	5	30	30	75
	C	83	96	660	850	640	2220	2200	1160	352	158	83	68	90
	D	82	131	420	1440	1180	3090	2500	2335	920	465	89	81	115

Note: In relation to zero low tide datum, the blocks were at the following depths:

A 6.3 ft.
B 3.3 ft.
C 0.3 ft.
D -2.7 ft.

a. poor block
b. specimen 9 mm long
c. specimen 16 mm long
d. specimen 22 mm long

Table from Johnson and Miller (Johnson and Miller 1935).

FOULING ORGANISMS

The groups of organisms which make major contributions to fouling in the Puget Sound area are the barnacles, the non-boring mollusks, and the bryozoa and hydroids. Of lesser significance are the algae and less commonly occurring forms such as brachiopods, annelid tube worms, tunicates, and some varieties of coelenterates.

Barnacles

The barnacles represent one of the more abundant forms of the area. They exist almost universally wherever there are suitable substrata for attachment. These forms, although not strictly intertidal animals, are most prevalent in the area near the zero low-tide datum where they frequently exist in heavily encrusting colonies.

SPECIES. According to Henry there are thirteen species of barnacles in Puget Sound which exhibit the following vertical zonation (Henry 1940):

High-tide region:	Chthamalus dalli Balanus glandula
Mid-tide region:	B. glandula B. cariosus *Mitella polymerus
Mid-tide to zero tide region:	B. crenatus B. cariosus
Minus-tide region:	B. cariosus B. crenatus B. nubilus B. rostratus alaskensis B. balanus pugetensis *B. engbergi
Sub-littoral zone:	B. crenatus B. nubilus B. rostratus alaskensis B. balanus pugetensis B. hesperius laevidomus *B. engbergi *Scalpellum columbianum
Pelagic forms:	Lepas anatifera L. pectinata pacifica

*Indicates least prevalent of the group.

PERIOD OF SETTLEMENT. Concerning the seasonal settlement of the cirripedia, Johnson and Miller at Friday Harbor, found two maxima of settlement, one in May and the other in September (Johnson and Miller 1935). This, however, was for one species only B. glandula. Hower, at Shelton, Washington, found a maximum period of settlement from 1 March to 15 May for B. glandula and B. crenatus (Hower 1938).

DEGREE OF ATTACK. Although the degree to which these forms will attach will show marked seasonal and local variation, a general year to year pattern marks the area as one in which heavy fouling from these forms is to be expected. Further information concerning degree of attack, size, abundance and occurrence of these forms may be obtained from the references (Henry 1940a, 1942; Rice 1930; Towler 1930; U.S. Navy Bureau of Yards and Docks 1951; Woreley 1930).

Mussels

The non-boring mollusks are mainly represented in the area by the mussel Mytilus edulis. This sessile form, usually existing with the barnacle communities, is most prevalent in the low tide zone.

PERIOD OF SETTLEMENT. According to Martin's work in the Bremerton area, the period of maximum settlement for Mytilus edulis was from about 1 April to 1 July at Seabeck and Keyport and from about 1 May to 6 August at Bremerton.

DEGREE OF ATTACK. Over the 12 and 14 month periods during which the investigations were made in the Bremerton area, the following counts comprised the total numbers of Mytilus edulis that attached to four square feet of exposed area at each locality (Martin 1938):

Bremerton, Standard Oil Dock	- 103
Bremerton, Navy Yard	- 643
Seabeck	- 5830
Keyport	- 993

There is a lack of information concerning horizontal distribution of these forms.

Bryozoa and Hydroids

Since they are so numerous and so difficult to observe, the degree to which the bryozoa and hydroids have contributed to fouling in the Puget Sound area has not received due consideration.

PERIOD OF SETTLEMENT. Hower's work at Shelton indicates a period of maximum settlement for encrusting bryozoa from mid-June to mid-September and occurrences of non-encrusting forms in May, June, September, November, and December (Hower 1938). For a complete classification of Puget Sound bryozoa, see The Bryozoa of Puget Sound and Adjacent Regions (Knox 1938), and List of Bryozoa from the Vicinity of Puget Sound (O'Donoghue and O'Donoghue 1925).

Algae

Information concerning the quantitative contributions of algae to fouling is lacking. However, one report on test panel operations in Puget Sound indicates traces of green algae in three instances. Consideration must be given to the fact that in no case were these panels exposed more than 8 months (U.S. Navy Bureau of Yards and Docks 1951).

MAMMALS

Certain mammals are known to occur in the Puget Sound area. A general description of the activities of the predominant species follows.

Whales, Dolphin, and Porpoise

The cetaceans are known to be mainly habitants of open ocean, however they have frequently been known to journey into the inland waters as far south as the Nisqually Reach area in the southernmost part of Puget Sound. Except for the "harbor porpoise," the "killer whale" and to a lesser extent the "humpback whale," their occurrence in the area is infrequent.

SPECIES. According to Scheffer and Slipp the following species of cetaceans have been observed within the confines of Puget Sound (Scheffer and Slipp 1948):

**Mesoplodon stejnegeri* True	- Stejnegar Beaked Whale
Grampus rectipinna (Cope)	- Killer Whale
Pseudorca crassidens (Owen)	- False Killer Whale
**Rhachianectes glaucus* (Cope)	- Gray Whale
Balaenoptera physalus (Linnaeus)	- Finback Whale
Balaenoptera acutorostrata Lacepede	- Little Piked Whale
Megaptera novaeangliae (Borowski)	- Humpback Whale
Delphinapterus leucas (Pallus)	- White Whale, Beluga
Phocoena vomerina (Gill)	- Harbor Porpoise

*Uncertain idenity

KILLER WHALES. The killer whales (blackfish), although recorded in Puget Sound at all seasons, are most frequently seen off Camano Island during the salmon and herring runs, the Tacoma area during the spring and fall months and in Tulalip Bay during the summer. Of a gregarious nature, they rove in "wolf packs," rarely remaining in one place more than a few minutes, and are especially active in shallows and river mouths after nightfall where they feed. Some local sources regard the "killer whale" as a nuisance and salmon predator while others defend it as a natural enemy of other fish predators such as harbor seals and birds.

HUMPBACK WHALES. The "humpback whale" is probably the most common of the large whales to enter the inland waters of the area. This whale, usually occurring alone, has been reported seen as far south as Henderson Inlet, and is probably the species seen from time to time in Elliott Bay.

PORPOISE. "Harbor porpoises" are the most common cetaceans of the area and occur during all seasons. Being less gregarious than the "killer whale" they are usually seen in pairs or small groups. Generally they avoid the shallows of the eastern side of the Sound where the water is muddy or brackish.

Seals

Harbor seals Phoca vitulina richardii which are quite common along the outer coast also occur within Puget Sound where they are known to frequent the shallow bays and tideflat areas. Invariably they will be found in places where it is impossible for an enemy to approach unseen, such as on rocks, sand bars or floating logs. They are strictly nonmigratory and can be found during all seasons wherever they occur (Scheffer and Slipp 1944).

REPRODUCTION. Important breeding grounds for the harbor seal can be found at the deltas of the Skagit, Stillaguamish, Snohomish, and Nisqually Rivers. Their pupping season, which occurs later in the inland waters than on the coast, is from about late June to early August (Scheffer and Slipp 1944).

PREDATION. Locally, the harbor seal is considered a nuisance and a fish predator. Scheffer and Sperry reported in 1931 that fishes made up 93.58 percent of the total volume of the stomach contents of 81 seals taken from 1927 to 1930 (Scheffer and Sperry 1931).

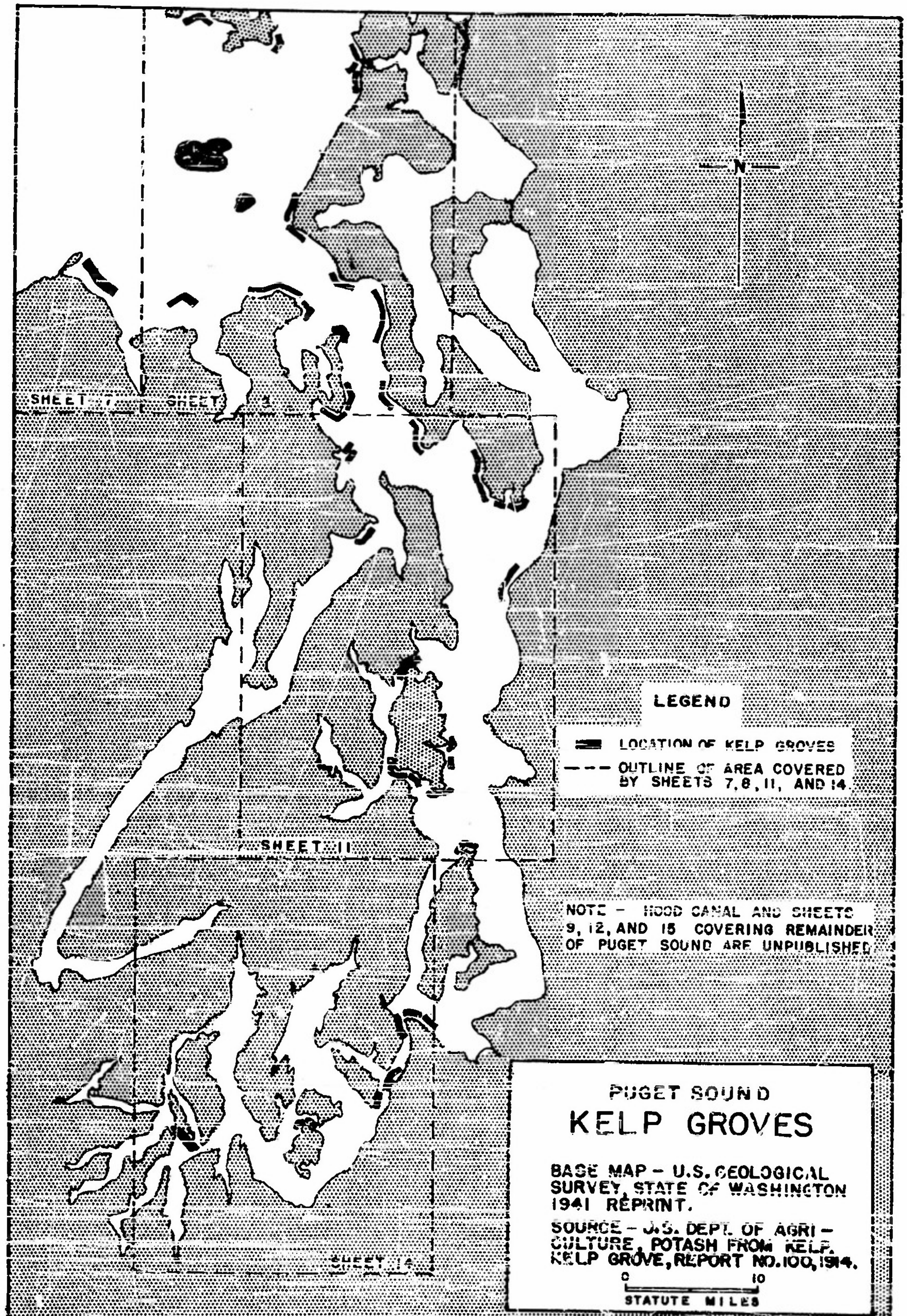
N
SHEET 7
SHEET 8
SHEET 11
SHEET 14
LEGEND
LOCATION OF KELP GROVES
OUTLINE OF AREA COVERED BY SHEETS 7, 8, 11, AND 14.
NOTE - HOOD CANAL AND SHEETS 9, 12, AND 15 COVERING REMAINDER OF PUGET SOUND ARE UNPUBLISHED
PUGET SOUND
KELP GROVES
BASE MAP - U.S. GEOLOGICAL SURVEY, STATE OF WASHINGTON 1941 REPRINT.
SOURCE - U.S. DEPT. OF AGRICULTURE, POTASH FROM KELP. KELP GROVE, REPORT NO. 100, 1914.
0
10
STATUTE MILES

Fig. 11-2

KELP BEDS

As the following illustrates, the occurrences of Kelp beds within Puget Sound is relatively uncommon.

Location

In Fig. 11-2 are shown the locations and extent of the Kelp beds in Puget Sound as recorded by the United States Department of Agriculture Survey in 1911 and 1912. For the most part these beds represent pure stands of the bladder kelp Nereocystis luetkeana. However in some areas of the Straits of Juan de Fuca a narrow bed of Macrocystis pyrifera will be found on the shoreward side of the Nereocystis bed. The major kelp beds of this region are either in the Strait of Juan de Fuca or the San Juan Islands with only a few scattered patches occurring in Puget Sound proper.

Abundance

It was estimated in the 1911 and 1912 investigations that about 390,000 tons of Kelp occur in the entire Puget Sound region of which only 3000 tons occur in that area south of Port Townsend. It should be noted this estimate is conservative and concerns mainly Nereocystis which is an annual plant (U.S. Department of Agriculture Bureau of Soils 1914).

Neither Nereocystis or Macrocystis grow above extreme low tide. They are most often found firmly attached to rocks preferably in water that is constantly in motion (Hurd 1916a, 1916b).

RED TIDE

A strikingly brown to reddish discoloration has frequently been observed in the Puget Sound waters particularly during the summer months. This phenomenon, called a "red tide" is the result of the multiplication of enormous numbers of pigmented zooplankton which give a marked discoloration to the water when present in sufficient concentrations.

Species

The organisms mainly responsible for these occurrences are the dinoflagellates Noctiluca scintillars, Gymnodinium splendens, Ceratium fusus and the ciliate protozoan Cyclotrichium. It should be noted that other forms may cause water discoloration but the above are the principal ones found in the area (Glud, et.al. 1947).

PLANKTON

Except for the area at the entrance to Hood Canal, plankton investigations in Puget Sound and adjacent waters have been almost entirely restricted to the waters of the San Juan Archipelago and the Strait of Juan de Fuca. Factual information on the species, abundance, distribution and seasonal occurrence of plankton in Puget Sound proper is lacking.

General Distribution of Plankton in Puget Sound

The work of Thompson and Phifer in June 1933 on the surface waters of Puget Sound from which the following summary was made, offers a general distribution of plankton in Puget Sound during the summer season.

1. Relative to waters east of Deception Pass the quantity of plankton decreased between Deception Pass and Camano Head.
2. South of Lowell Point the diatom-dominant plankton changes to one composed mainly of thecate dinoflagellates of the genera Peridinium, Dinophysis, and Ceratium together with ciliates of the genera Favella, Helicostomella, Tintinnus. and Tintinnopsis. This type of plankton continues to Dash Point.
3. The Plankton in the Point Defiance section of Puget Sound was dominated by diatoms.
4. From Point Defiance to Foulweather Bluff via Colvos Passage the plankton was composed mainly of dinoflagellates and cilliates.
5. Across Admiralty Inlet to Possession Sound the plankton was non-descript consisting of diatoms, dinoflagellates, and cilliates in about equal portions together with a few larval forms of zooplankton.

(Thompson and Phifer 1936).

Distribution of Plankton at the Entrance to Hood Canal

According to plankton investigations made at the entrance to Hood Canal by Dempster in 1934, the following results were revealed.

1. The copepod fauna was mainly represented by Pseudocalanus elongatus [now P. minutus], Oithona helgolandica now O. similis and Corycaeus affinis. Also present were the copepods Acartia longiremis, A. clausii, Calanus finmarchicus, Microsetella rosea, Tortanus discaudatus and Metridia lucens.
2. Crustacean larvae were evenly distributed throughout the entire year and contributed a substantial percentage to the zooplankton of the locality. The copepod nauplii were the dominant forms during the entire year except for May and June when the crab larvae predominated.

3. Copepod eggs were plentiful in all plankton hauls and most abundant during March and April.
4. Amphipods were most often encountered in the winter plankton hauls and were most numerous in the deep zones.
5. Sagitta was numerous in the deep samples taken during the winter and spring months.
6. Pelagic tunicates were frequently found but never abundant.
7. Rotifers appeared sparsely.
8. Medusae were found mostly in June and July. The most important species was Phialidium gregarium.
9. The tintinnoinea were mainly represented by Stenosomella expansa, S. ventricosa and Tintinnopsis gracialis.
10. The dinoflagellates were mainly represented by Peridinium depressum which was prominent from April to January; Ceratium fusus which was prominent in August, October and December and Noctiluca scintillans which was prominent from June to December.
11. The diatoms were represented by twenty-four genera and fifty-two species. The prominent winter forms were Coscinodiscus centralis, C. excentricus, Arachnoidiscus ehrenbergii and Biddulphia arctica. Skeletonema costatum, Nitzschia seriata and Chaetoceros species were common during the remainder of the year. Several diatom forms bloomed only for short periods and were lacking or unimportant the remainder of the year.

(Dempster 1938). Species revision from (Davis 1949).

AMBIENT NOISE

No information concerning measurements of ambient noise in Puget Sound is known to be available. However, many of the organisms which have been classed as noisemakers in other areas are also known to be present in Puget Sound and it can be assumed that they utilize their noise making habits here as elsewhere.

POISONOUS MARINE LIFE

Three forms of marine life in Puget Sound are known to possess certain toxic properties which may have unpleasant or possibly fatal effects on humans. The following is a brief discussion of these forms.

Jellyfish

Common to the waters of Puget Sound is the large dark orange or reddish jellyfish Cyanea capillata. Suspended from the outer margin of this organism are numerous long thread-like tentacles which are liberally provided with stinging cells (nematocysts) that are capable of injecting a poisonous material into the skin of a victim.

EFFECTIVENESS OF STING. Depending upon the degree of contact and the sensitiveness of the skin, the effect of the sting will vary. However, there are instances on record, as Neal Carter points out, in which great discomfort has resulted.

> Assuming the skin of their arms and hands was sufficiently weathered to be non-sensitive they took no precautions and after about 10 minutes the engineer suffered an intense itching of the feet followed in about 20 minutes by a feeling of compression around the ribs.....the itching of the feet was so intense that work had to be stopped and the men sought any kind of relief..... in about 2 hours their distress ceased leaving a clammy and exhausted feeling that persisted another 30 minutes.
>
> (Carter 1943).

Fish Spines

It is common knowledge that certain varieties of fish are equipped with sharp dorsal spines capable of inflicting deep punctures on persons coming into contact with them. Fish of this type which are common to the Puget Sound area are the species rockfish, genus Sebastodes, the ratfish Hydrolagus colliei and the dogfish Squalus suckleyi.

NATURE OF WOUND. There apparently is considerable confusion regarding the exact nature of the spines of these fishes, and the wounds they inflict. The general opinion in some cases is that these wounds become infected through introduction of bacteria from the fish slime. However, in the case of the ratfish, it has been determined that certain venomous properties can be associated with its dorsal spine (Halstead and Bunker 1952).

Gonyaulax

It is indicated in other areas that instances of human poisoning have resulted from consuming sea food which had been feeding on species of the red tide organism, gonyaulax. Species of this dinoflagellate are not found in significant abundance in Puget Sound since it is probable that these forms are deleteriously affected by brackish water (Glud, et.al. 1947).

Appendix 11-A

PRINCIPAL FISHING AREAS AND MAJOR FISH AND SHELLFISH TAKEN FROM EACH AREA

	Oysters	Chinook Salmon	Chum Salmon	Pink Salmon	Silver Salmon	Sockeye Salmon	Flounder	True Cod	Ling Cod	Rock Fish	Black Rock	Sole	Dover Sole	English Sole	Rock Sole	Sand Sole	Petrale Sole
Admiralty Inlet		X	X	X	X	X											
Anacortes										X							
Bainbridge Island																	
Bangor																	
Bremerton							X	X	X	X		X		X			
Camano Island																	
Carr Inlet							X	X	X	X		X		X			
Case Inlet										X							
Cove																	
Deception Pass																	
Discovery Bay		X	X	X	X		X	X	X				X	X		X	
Dungeness								X	X								
Dyes Inlet																	
East Passage		X	X	X	X												
Eglon																	
Elliott Bay																	
Fletcher Bay																	
Hales Passage																	

	Perch	Silver Smelt	Scrap Fish	Dog Shark	Skate	Candle Fish	Herring	Clams	Crabs	Squid	Shrimp	Scallops	Octopus	Steelhead	Ratfish
Admiralty Inlet															
Anacortes							X	X	X						
Bainbridge Island							X								
Bangor								X							
Bremerton	X	X					X	X			X		X		
Camano Island								X							
Carr Inlet	X	X						X		X			X		
Case Inlet	X	X													
Cove												X			
Deception Pass		X													
Discovery Bay	X				X			X	X				X		X
Dungeness		X							X						
Dyes Inlet		X													
East Passage															
Eglon							X								
Elliott Bay											X				
Fletcher Bay									X						
Hales Passage							X								

PRINCIPAL FISHING AREAS AND MAJOR FISH AND SHELLFISH TAKEN FROM EACH AREA (continued).

	Oysters	Chinook Salmon	Chum Salmon	Pink Salmon	Silver Salmon	Sockeye Salmon	Flounder	True Cod	Ling Cod	Rock Fish	Black Sole	Sole	Dover Sole	English Sole	Rock Sole	Sand Sole	Petrale Sole	Perch	Silver Smelt	Scrap Fish	Dog Shark	Skate	Candle Fish	Herring	Clams	Crabs	Squid	Shrimp	Scallops	Octopus	Steelhead	Ratfish
Holmes Harbor																								x								
Hood Canal	x	x	x	x	x																											
Kilisut Harbor																			x					x								
Kingston							x	x	x	x		x	x	x			x	x			x	x	x							x		x
Lilliwaup																									x							
Meadow Point		x	x	x	x																											
Nisqually River		x	x		x																											
Nooksack River		x	x	x	x	x																										
Oak Bay																									x							
Oak Harbor																												x				
Olympia	x																	x	x					x	x			x				
Penn Cover																			x													
Point Defiance		x																														
Point No Point		x	x	x	x																											
Port Gamble																									x							
Port Gardner		x	x	x	x	x	x	x	x	x	x	x	x	x	x			x				x	x	x	x	x		x				
Port Ludlow																									x				x	x		
Port Madison																			x						x							
Port Susan		x	x	x	x	x	x	x	x	x		x		x				x								x						

PRINCIPAL FISHING AREAS AND MAJOR FISH AND SHELLFISH TAKEN FROM EACH AREA (continued).

	Oysters	Chinook Salmon	Chum Salmon	Pink Salmon	Silver Salmon	Sockeye Salmon	Flounder	True Cod	Ling Cod	Rock Fish	Black Rock	Sole	Dover Sole	English Sole	Rock Sole	Sand Sole	Petrale Sole	Perch	Silver Smelt	Scrap Fish	Dog Shark	Skate	Candle Fish	Herring	Clams	Crabs	Squid	Shrimp	Scallops	Octopus	Steelhead	Ratfish
Port Townsend								x	x	x		x													x							
Poulsbo																			x						x							
Quartermaster Harbor																			x					x								
Rolling Bay		x	x	x	x																				x							
Saratoga Passage					x		x	x	x	x		x	x	x	x	x		x			x	x								x		x
Seattle																								x								
Shelton																			x													
Skagit Bay		x	x	x	x	x	x	x	x	x		x												x		x						x
Skagit River		x	x	x	x	x																										
Skokomish River		x	x		x																											
Swinomish Slough																			x													
Tacoma							x	x	x	x		x		x	x		x	x		x		x		x			x			x		
Triangle Cove																			x													
Utsalladdy																			x													
Vashon Island																									x							
West Beach		x	x	x	x	x			x					x							x	x										x
West Passage		x	x		x																											
Whidbey Island																									x							
White River		x	x		x																				x						x	

Information summarized from several sources (Washington State Department of Fisheries n.d.b, n.d.c, 1952e).

Appendix 11-B

SUMMARY OF OPERATING UNITS IN THE PUGET SOUND AREA, 1949.*

TYPE OF UNIT	NUMBER
Fishermen:	
On vessels	4,672
On boats and shore	2,742
Total	7,414
Vessels, Motor	956
Net tonnage	20,085
Boats:	
Motor	1,266
Other	394
Accessory boats	296
Apparatus:	
Purse seines and Lampara nets	
Pilchard	-
Length, yards	-
Salmon	296
Length, yards	185,000
Haul seines	135
Length, yards	12,800
Gill nets:	
Salmon	696
Square yards	1,134,750
Shark	1,535
Square yards	1,262,250
Smelt.	-
Square yards	-
Lines:	
Trawl, set or hand	31,618
Hooks	639,652
Troll:	
Salmon	3,564
Hooks	17,820
Tuna	605(1)
Hooks	605
Pound nets	7(2)
Brush weirs	1
Reef nets	137
Dip nets	38
Beam trawls	6
Yards at mouth	55

TYPE OF UNIT	NUMBER
Otter trawls	162
Yards at mouth	2,400
Traps:	
Crab	18,300
Crawfish	-
Octopus	350
Shrimp	350
Dredges, tongs and by hand	41
Shovels	375

* Data pertains to all vessels whose home port is in the Puget Sound district, e.g. United States waters inside Cape Flattery.

(1) Used only by vessels that trolled or fished exclusively for tuna. Does not include Tuna gear used by vessels that also trolled for salmon.

(2) Fished only on Indian Reservations.

Data from Fishery Statistics of the United States, 1949 (Anderson and Peterson 1952).

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1926. Medusae of the San Juan Archipelago. Thesis, University of Washington, Seattle, Washington, 174 pages.
(Notes on distributions and description of forms.)

Gersbacher, W. M. and Maggie Denison
1930. Experiments with Animals in Tide Pools. Publications Puget Sound Biological Station, vol. 7, pp. 209-215.
(Study made in the San Juan Area. Correlates reactions of tide pool animals to changes of physical conditions.)

Gilbert, Charles H.
1889. Description of a New Species of Bathymaster B. jordani From Puget's Sound and Alaska. Proceedings U.S. National Museum, vol. 11, p. 554.

1912-25. Contributions to the Life History of the Sockeye Salmon. Reports of the British Columbia Commissioner of Fisheries.
(Mainly concerns life history of the Pacific sockeye salmon.)

Gilbert, Charles H. and Joseph C. Thompson
1905. Notes on the Fishes of Puget Sound. Proceedings of the U.S. National Museum, vol. 28, no. 1414, pp. 973-987.
(Mainly descriptive.)

Glud, John B., Vance Tarter, Trevor Kincaid, and David C. McMillin
1947. Red Tide. Washington State Department of Fisheries, State Shellfish Laboratory, Gig Harbor, Washington, 3 pages (mimeographed).
(A regional analysis including a discussion of the toxic effects of red tide organisms on shellfish with particular reference to the oysters in Oyster Bay.)

Gran, H. H. and E. C. Angst
1931. Plankton Diatoms of Puget Sound. Publications Puget Sound Biological Station, vol. 7, pp. 417-516.
(Description and taxonomy of diatoms found in vicinity of Friday Harbor.)

Gran, H. H. and Thomas G. Thompson
1930. The Diatoms and the Physical and Chemical Conditions of the Sea Water of the San Juan Archipelago. Publications Puget Sound Biological Station, vol. 7, pp. 169-204.
(Correlates diatom occurrence with physical and chemical conditions of the water.)

Griffen, B. B.
1897. Adaptation of the Shell of Placuanomia to that of Saxidomus, with Remarks on Shell Adaptation in General. Transactions of the New York Academy of Sciences, vol. 16, pp. 77-81.
(Concerns observations made near Port Townsend.)

1898. Description of Some Nemerteans of Puget Sound and Alaska. Annals of the New York Academy of Science, vol. 11, no. 10, pp. 193-217.

Griffen, Eldon
1941. Oysters Have Eyes. Wilberlilla Publishers, Seattle, Washington, 53 pages (processed).
(Pertinent to Puget Sound oyster farming. General information.)

Guberlet, John E.
1928. Observations on the Spawning Habits of Melibe leonia (Gould). Publications Puget Sound Biological Station, vol. 6, pp. 263-270.
(Observations were made on Brown Island, San Juan Archipelago.)

1934. Observations on the Spawning and Development of Some Pacific Annelids. Proceedings of the Fifth Pacific Science Congress, pp. 4213-4220.
(Includes information on the spawning habits of polychaetous annelids of Puget Sound.)

Guberlet, John E. and Melville H. Hatch
n.d. The Distribution of Bottom Animals in Puget Sound and Adjacent Waters. [1931-1941]. Manuscript on file in the Department of Zoology, University of Washington, Seattle, Washington. (Unpublished.)
(A detailed and cross referenced list and analysis of all animals dredged by the Catalyst during the years from 1931 to 1941.)

Hacker, Robert Lester
1934. The Method of Boring, Spawning Season, Larval Stages, and Food of Pholas (Zirfaea) pilsbryi Lowe. Thesis, University of Washington, Seattle, Washington, 23 pages.

Halstead, Bruce W. and Norman C. Bunker
1952. The Venom Apparatus of the Ratfish, Hydrolagus colliei. Copeia 1952, no. 3, pp. 128-138.
(Anatomical and physiological considerations of venom apparatus as associated with the spines of the ratfish which is common to Puget Sound.)

Hammond, J. P.
1886. Fish in Puget Sound. Bulletin of the United States Fish Commission, vol. VI, pp. 195-196.
(Description of the local fishery from 1869 to 1877.)

Harrington, N. R. and B. B. Griffin
1898. Notes Upon the Distribution and Habits of Some Puget Sound Invertebrates. Transactions of the New York Academy of Sciences, vol. 16, pp. 152-165.
(Analysis by areas and zones within each area.)

Hartge, Lena A.
1928. Nereocystis. Pubet Sound Biological Station Publications, vol. 6, pp. 207-237.
(Contains the history, general description, and methods of culture of the Puget Sound bladder kelp Nereocystis.)

Henry, Dora Priaulx
1940a. The Cirripedia of Puget Sound with a Key to the Species. University of Washington Publications in Oceanography, vol. 4, no. 1, pp. 1-48.
(Morphological considerations and a key to the species.)

1940b. Notes on Some Pedunculate Barnacles From the North Pacific. Proceedings of the United States National Museum, vol. 88, no. 3081, pp. 225-236.
(Includes a description of barnacles taken in Puget Sound.)

Henry, Dora Priaulx

1942. Studies on the Sessile Cirripedia of the Pacific Coast of North America. University of Washington Publications in Oceanography, vol. 4, no. 3, pp. 95-134.
(Morphological, taxonomic and ecological considerations. Includes Puget Sound forms.)

Hopkins, A. E., Paul S. Galtsoff, and H. C. McMillin

1931. Effects of Pulp Mill Pollution on Oysters. U.S. Department of Commerce, Bureau of Fisheries, Bulletin no. 6, pp. 125-186.
(Concerns the effects of sulfite waste liquors on oysters in Oakland Bay.)

Horn, Agnes D.

1932. An Ecological Survey of the Marine Life of Lone Tree Point, Skagit Bay, Puget Sound. Thesis, University of Washington, Seattle, Washington, 70 pages.
(Lists forms of the locality with information on characteristics of each.)

Hower, John H.

1938. The Seasonal Settlement of Bankia, Limnoria, Barnacles, Bryozoa, and other Sessile Organisms at Shelton, Washington. Thesis, University of Washington, Seattle, Washington, 53 pages.

Humphrey, R. R. and R. W. Macy

1930. Observations on Some of the Probable Factors Controlling the Size of Certain Tide Pool Snails. Publications Puget Sound Biological Station, vol. 7, pp. 205-208.
(Observations made in San Juan area.)

Hurd, Annie May

1916a. Codium dimorphum. Puget Sound Marine Station Publications, vol. 1, no. 19, pp. 211-219.
(Considers habitat and general description of Puget Sound algae C. dimorphum.)

1916b. Codium mucronatum. Puget Sound Marine Station Publications, vol. 1, no. 12, pp. 109-135.
(Morphological considerations of marine algae C. mucronatum which is commonly found in Puget Sound.)

1916c. Factors Influencing the Growth and Distribution of Nereocystis luetkeana. Puget Sound Marine Station Publications, vol. 1, no. 17, pp. 185-198.
(Work done at Friday Harbor. Mention made of kelp found in San Juan Channel.)

Hurd, Annie May
1917. Winter Condition of Some Puget Sound Algae. Puget Sound Marine Station Publications, vol. 1, no. 29, pp. 341-348.
(Collections from Fort Lawton and Lincoln Beach. Notes on seasonal variation of flora.)

1919. The Relation between the Osmotic Pressure of Nereocystis and the Salinity of the Water. Publications Puget Sound Biological Station, vol. 2, no. 2, pp. 183-193.

Igelsrud, Iver, Thomas G. Thompson, and Benj. M. G. Zwicker
1938. The Boron Content of Sea Water and of Marine Organisms. American Journal of Science, 5th series, vol. 35, no. 205, pp. 47-63.
(Some of the analysis were made in the Puget Sound area. Contains information on boron content of marine algae from San Juan area.)

Jao, Chin-Chin
1936. New Marine Algae From Washington. Papers of the Michigan Academy of Science, Arts and Letters, vol. 22, pp. 99-116.
(Description of species of marine algae taken in San Juan Islands area.)

1948. The Marine Myxophceae in the Vicinity of Friday Harbor, Washington. Botanical Bulletin of Academia Sinica, vol. 2, pp. 161-177.
(Notes on occurrence and a description of species.)

Johnson, H. P.
1901. The Polychaeta of the Puget Sound Region. Proceedings Boston Society Natural History, vol. 29, no. 18, pp. 381-437.
(General description of species including diagrams.)

Johnson, Martin W.
1931. Seasonal Distribution of the Plankton at Friday Harbor, Washington. Thesis, University of Washington, Seattle, Washington, 77 pages.

1932. Seasonal Distribution of Plankton at Friday Harbor, Washington. University of Washington Publications in Oceanography, vol. 1, no. 1, pp. 1-38.
(Discussion of zooplankton and diatoms.)

1934. The Life History of the Copepod <u>Tortanus discaudatus</u> (Thompson and Scott). Biological Bulletin, vol. 67, no. 1, pp. 182-200.
(Morphological consideration and life history. Only species of the genus recorded in Puget Sound.)

Johnson, Martin W.
1935. Seasonal Migration of the Wood-Borer Limnoria lignorum (Rathke) at Friday Harbor, Washington. Biological Bulletin, vol. 69, no. 3, pp. 427-438.

1943. Studies on the Life History of the Marine Annelid Nereis vexillosa. Biological Bulletin, vol. 84, no. 1, pp. 106-114. (Portion of work done at Friday Harbor, Washington.)

Johnson, Martin W. and Robert C. Miller
1935. The Seasonal Settlement of Shipworms, Barnacles, and Other Wharf-Pile Organisms at Friday Harbor, Washington. University of Washington Publications in Oceanography, vol. 2, no. 1, pp. 1-18.

Jordan, D. S. and C. H. Gilbert
1881a. Description of Two New Species of Flounders Parophrys vetulus and Hippoglasoides elassodon from Puget's Sound. Proceedings U.S. National Museum, vol. 3, pp. 276-280.

1881b. Description of A New Species of Nemichthys Nemichthys avocetta from Puget Sound. Proceedings U.S. National Museum, vol. 3, pp. 409-410.

1881c. Description of A New Species of Paralepis Paralepis coruscans from the Straits of Juan de Fuca. Proceedings U.S. National Museum, vol. 3, pp. 411-413.

1894. Note on the Wall-eyed Pollack Pollachius chalcogrammus fucensis of Puget Sound. Proceedings U.S. National Museum, vol. 16, no. 939, pp. 315-316.
(Mainly descriptive.)

Jordan, David Starr and Edwin Chapin Starks
1895. The Fishes of Puget Sound. Proceedings California Academy of Sciences, 2d series, vol. 5, pp. 785-852.
(General description, including plates, of fishes collected near Port Orchard.)

Keen, Myra A. and John C. Pearson
1952. Illustrated Key to West North American Gastropod Genera. Stanford University Press, Stanford, California, 39 pages.

Kenyon, Karl W. and Victor B. Scheffer
1953. The Seals, Sea Lions, and Sea Otter of the Pacific Coast. U.S. Fish and Wildlife Service, Wildlife Leaflet no. 344.
(A brief description of species and habits.)

Kincaid, Trevor
1919. An Annotated List of Puget Sound Fishes. State of Washington Department of Fisheries, Seattle, Washington, 51 pages.

1920. The Edible Clams of Puget Sound. State of Washington Department of Fisheries and Game, Twenty-Eighth and Twenty-Ninth Annual Reports of the State Fish Commissioner to the Governor of the State of Washington, pp. 47-59.
(Includes economic considerations.)

Knox, Cammeron
1938. The Bryozoa of Puget Sound and Adjacent Regions. Thesis, University of Washington, Seattle, Washington, 360 pages.
(Anatomical and taxonomic considerations of Puget Sound Bryozoa.)

Lloyd, Lowell Clyde
1938. Some Digenetic Trematodes From Puget Sound Fish. The Journal of Parisitology, vol. 24, no. 2, pp. 103-133.
(Taxonomy and description of parasitic fauna of Puget Sound fishes.)

Martin, George W.
1938. The Seasonal Settlement of Bankia, Limnoria, Barnacles and other Wharf Pile Organisms in the Vicinity of Bremerton, Washington. Thesis, University of Washington, Seattle, Washington, 33 pages.

McCutcheon, Rob. S., Louis Arrigoni, and Louis Fischer
1949. A Phytochemical Investigation of the Kelps Cymathaere triplicata, Hedophyllum sessile and Egregia menziesii. Journal of the American Pharmaceutical Association, Scientific Edition, vol. 38, no. 4, pp. 196-200.
(Chemical analysis of some of the kelps found near Friday Harbor.)

McDonald, Lucile
1952a. Puget Sound Marine Life. The Seattle Times, Sunday, July 6, 1952.
(Exceptionally rich marine life in Puget Sound. Many shores in other parts of the world lack variation for hundreds of miles but in Puget Sound we have, within a reasonably small area, salt water beaches of all types--rocky, sandy and muddy. We have mouths of fresh water streams, warm saline bays and places where the currents are cold and move swiftly. Shallows and deep canyons. Each supports its own population. Zoogeography.)

McDonald, Lucile
1952b. Puget Sound's Rich Sea-Food Harvest. The Seattle Times, Sunday, July 13, 1952.
(The various food fish and animals of the Sound are listed. The statement is made that no animal in the Sound is dangerous, except perhaps, the large red or brown jellyfish.)

McKernan, Donald L., Vance Tarter, and Roger Tollefson
1949. An Investigation of the Decline of the Native Oyster Industry of the State of Washington, with Special Reference to the Effects of Sulfite Pulp Mill Waste of the Olympia Oyster Ostrea lurida. State of Washington Department of Fisheries, Biological Report no. 49A, pp. 115-165.
(The principal native oyster producing bays of Puget Sound are all located in the southern extremity, below the Narrows. Principal pollution is from the pulp mill by Oakland Bay.)

McLean, A. J.
1921. Effects of Thyroid and Iodine Feeding upon the Metamorphosis of two Species of Crab. Publications Puget Sound Biological Station, vol. 3, no. 61, pp. 93-103.
(Specimens used in experiments were the Puget Sound crabs Cancer magister and C. gracilis.

Miles, Ward R.
1918. Experiments on the Behavior of Some Puget Sound Shore Fishes (Blenniidae). Publications Puget Sound Biological Station, vol. 2, no. 37.
(Considers responses of Blenniidae to various stimuli.)

Miller, R. C.
1939. Plankton Investigations at the University of Washington. Proceedings of the Sixth Pacific Science Congress, vol. 3, pp. 585-586
(Presents a summary of Plankton investigations. Conducted in or near Puget Sound.)

Miller, Robert C., Ellsworth D. Lumley, and F. S. Hall
1935. Birds of the San Juan Islands, Washington. Murrelet, vol. 16, pp. 51-65.
(Includes a list of all birds of which specimens are known to have been taken in the Islands or for which there are definite sight records by competent ornithologists.)

Miller, R. C. and Earl R. Norris
1939. Some Enzymes of the Northwest Shipworm Bankia setacea. Proceedings of the Sixth Pacific Science Congress, vol. 3, pp. 615-616.
(B. setacea common to Puget Sound.)

Monda, George J.
1926. The Isopoda of Puget Sound and Adjacent Waters. Thesis, University of Washington, Seattle, Washington, 104 pages. (Damage to piles and submerged timbers done by these crustaceans.)

Moore, Clarita L.
1927. Simple Ascidians of the Friday Harbor, Washington, Region. Thesis, University of Washington, Seattle, Washington, 71 pages. (The tunicates or ascidians are common along the shore, on wharf piles, and at considerable depths.)

Moore, Caroline S. and Laura B. Moore
1930. Some Desmids of the San Juan Islands. Publications Puget Sound Biological Station, vol. 7, pp. 289-335. (Taxonomy and description.)

Muenscher, Walter L. C.
1915a. Ability of Seaweeds to Withstand Desication. Puget Sound Marine Station Publications, vol. 1, no 4, pp. 19-23. (Work done on species of Chlorophyceae, Phaeophyceae and Rhodophyceae at Friday Harbor.)

1915b. A Study of Algal Associations of San Juan Island. Puget Sound Marine Station Publications, vol. 1, no. 9, pp. 59-84. (Geographical distribution and vertical zonation of algae on San Juan Island.)

1916. Distribution of Shore Algae on Shaw Island. Puget Sound Marine Station Publications, vol. 1, no. 18, pp. 199-210. (A list of 103 species of algae.)

1917. A Key to Phaeophyceae of Puget Sound. Puget Sound Marine Station Publications, vol. 1, no. 25, pp. 249-285.

Myers, M. E.
1924. The Mucilage Canals of Nereocystis. Thesis, University of Washington, Seattle, Washington, 14 pages. (Description of structure of the Puget Sound bladder kelp Nereocystis.)

Norris, Earl R., Mary K. Simeon, and Hal B. Williams
1937. The Vitamin B and Vitamin C content of Marine Algae. The Journal of Nutrition, vol. 13, no. 4, pp. 425-433. (Includes information of a number of marine algae taken in San Juan Islands.)

Nightingale, H. W.
1936. Red Water Organisms--Their Occurrence and Influence Upon Marine Aquatic Animals With Special Reference to Shellfish in the Waters of the Pacific Coast. The Argus Press, Seattle, Washington, 24 pages.
(Notes on the occurrence of Gymnodinium splendens in Oakland and Oyster Bays and its effects on the shellfish.)

1938. Concerning the Effects of Waste Sulfite Liquor Upon Fish Life With Special Reference to Early Stages of the Chinook Salmon. The Argus Press, Seattle, Washington, 34 pages.
(Considers the effects of sulfite waste liquors on salmon fingerlings.)

O'Donoghue, Chas. H.
1925. Notes on Certain Bryozoa in the Collection of the University of Washington. Publications Puget Sound Biological Station, vol. 5, pp. 15-23.
(Taxonomic descriptions of Puget Sound Bryozoa.)

O'Donoghue, Chas. H. and Elsie O'Donoghue
1925. List of Bryozoa from the Vicinity of Puget Sound. Publications Puget Sound Biological Station, vol. 5, pp. 91-108.
(Taxonomy of Puget Sound Bryozoa.)

Oldroyd, Ida Shepard
1918. A Summers Collection at Friday Harbor. The Nautilus, vol. 31, no. 3, pp. 95-98.
(Mixed list of animals collected during a summer at Friday Harbor.)

1924. Marine Shells of Puget Sound and Vicinity. Publications Puget Sound Biological Station, vol. 4, pp. 1-271.
(Contains complete description of Puget Sound shell types. Complete to plates.)

Olson, A. Walter, Jr.
1949. Some Aspects of the Fishing Industry in Washington State. Thesis, College of Puget Sound, Tacoma, Washington.

Orlob, Gerald T., M. D. Anderson, and D. L. Hansen
1949. An Investigation of Pollution in Port Gardner Bay and the Lower Snohomish River. The Washington State Pollution Control Commission, 25 pages (mimeographed.)
(Sulfite waste liquor, bacteria, fish kills, river flow, and oxygen concentrations are considered in the problem.)

Osterud, H. L.
1918. Preliminary Observations on the Development of Leptasterias hexactis. Publications Puget Sound Biological Station, vol. 2, no. 32, pp. 1-16.
(Considers the embryological development of the starfish Leptasterias hexactis common to Puget Sound.)

Pease, Vinnie A.
1917. North Pacific Coast Species of Desmarestia. Puget Sound Marine Station Publications, vol. 1, no. 31, pp. 383-396.
(Taxonomic considerations of species of Desmarestia which are found in the Puget Sound region.)

Perry, Edna M.
1916. Distribution of Certain Invertebrates on a Restricted area of Sea Bottom. Puget Sound Marine Station Publications, vol. 1, no. 15, pp. 174-176.
(Area studied is northeast of Brown Island in the San Juan Archipelago.)

Phifer, Lyman D.
1929. Littoral Diatoms of Argyle Lagoon. Publications Puget Sound Biological Station, vol. 7, pp. 137-149.
(Considers abundance, lateral distribution and physiological factors of diatoms in Argyle Lagoon.)

1933. Seasonal Distribution and Occurrence of Planktonic Diatoms at Friday Harbor, Washington. University of Washington Publications in Oceanography, vol. 1, no. 2, pp. 39-81.

1934a. Periodicity of Diatom Growth in the San Juan Archipelago. Proceedings of the Fifth Pacific Science Congress, pp. 2047-2049.
(Correlates environmental factors with diatom growth.)

1934b. Vertical Distribution of Diatoms in the Strait of Juan de Fuca. University of Washington Publications in Oceanography, vol. 1, no. 3, pp. 83-96.
(Concerns the vertical and horizontal distribution of diatoms.)

1935. Phytoplankton of East Sound, Washington. University of Washington Publications in Oceanography, vol. 1, no. 4, pp. 97-110.
(Concerns the vertical and horizontal distribution of phytoplankton in East Sound.)

Pierron, R. P. and Y. C. Huang
1926. Animal Succession on Denuded Rocks. Publications Puget Sound Biological Station, vol. 5, pp. 149-157.
(Observations made on Brown Island in San Juan Archipelago.)

Pilsbry, A. H.
1921. Barnacles of the San Juan Islands. Proceedings of the United States National Museum, vol. 59, pp. 111-115.
(General description with a key to the species.)

Powers, Edwin B.
1920. The Variation of the Condition of Sea Water, Especially the Hydrogen Ion Concentration, and its Relation to Marine Organisms. Publications Puget Sound Biological Station, vol. 2, no. 54, pp. 369-385.
(Water samples taken near Biological Station at Friday Harbor.)

1921. Experiments and Observations on the Behavior of Marine Fishes Toward the Hydrogen-Ion Concentration of the Sea Water in Relation to Their Migratory Movements and Habitat. Publications Puget Sound Biological Station, vol. 3, no. 57, pp. 1-21.
(Observations made in San Juan area.)

1939. Chemical Factors Affecting the Migratory Movements of the Pacific Salmon. The Migration and Conservation of Salmon, Edited by Forest Ray Moulton, The Science Press, Lancaster, Pennsylvania, pp. 72-85.
(Mainly concerns the Pacific Salmon while in Alaskan waters. Pertinent to the migration of salmon in Puget Sound.)

Powers, Edwin B. and Lula Mae Shipe
1928. The Ratio of Oxygen Absorption by Certain Marine Fishes as Affected by the Oxygen Content and Carbon Dioxide Tension of the Sea Water. Publications Puget Sound Biological Station, vol. 5, pp. 365-369.
(Experiments were conducted on herring, salmon, and perch. Work done at Friday Harbor.)

Pritchard, Andrew L.
1930. Pacific Salmon Migration: The Tagging of the Pink Salmon and the Chum Salmon in British Columbia in 1928. Canada Biological Board, Bulletin no. 14, pp. 1-17.
(Includes information pertinent to Puget Sound salmon migration.)

1932. Pacific Salmon Migration: The Tagging of the Pink Salmon and the Chum Salmon in British Columbia in 1929 and 1930. Canada Biological Board, Bulletin no. 31, pp. 1-16.
(Includes information pertinent to Puget Sound salmon migration.)

1934. Pacific Salmon Migration: The Tagging of the Coho Salmon in British Columbia in 1929 and 1930. Canada Fisheries Research Board, Bulletin no. 40, pp. 1-24; Bulletin no. 41, pp. 1-31.
(Includes information pertinent to Puget Sound salmon migration.)

Pritchard, Andrew L. and Allan C. DeLacy
1944. Migration of Pink Salmon Oncorhynchus gorbuscha in Southern British Columbia and Washington in 1943. Canada Fisheries Research Board, Bulletin no. 66, pp. 1-23.
(Summarizes results of tagging experiments. Areas covered include: Point Roberts, Lummi Island, Bellingham Bay, Rosario Strait, West Beach (Whidbey Island), Skagit Bay, Port Susan, Admiralty Inlet, Lower Puget Sound-south of Port Susan, Stuart Island, Salmon Banks, Dungeness River, Sooke, Port Renfrew, Port Angeles, Neah Bay and Cape Flattery, Swiftsure Bank. Charts included.)

Rice, Lucile
1930. Peculiarities in the Distribution of Barnacles in Communities and their Probable Causes. Publications Puget Sound Biological Station, vol. 7, pp. 249-257.
(Correlates distribution of Balanus communities with environmental conditions. Study made in San Juan area.)

Rich, Willis H.
1939. Local Populations and Migration in Relation to the Conservation of Pacific Salmon in the Western States and Alaska. The Migration and Conservation of Salmon, Edited by Forest Ray Moulton, The Science Press, Lancaster, Pennsylvania, pp. 45-50.
(Concerns the migratory characteristics of the Pacific Salmon. Pertinent to the migration of salmon in Puget Sound.)

Riddle, Matthew C.
1917. Early Development of the Chinook Salmon. Puget Sound Marine Station Publications, vol. 1, no. 28, pp. 319-339.
(Description of sperm, egg, segmentation, formation of blastoderm and periblast, gastrulation and hatching.)

Rigg, George B.
1917. Seasonal Development of Bladder Kelp. Puget Sound Marine Station Publications, vol. 1, no. 27, pp. 309-318.
(Observations include various Puget Sound localities.)

Rigg, George B. and R. C. Miller
1949. Intertidal Plant and Animal Zonation in the Vicinity of Neah Bay, Washington. Proceedings of the California Academy of Sciences, 4th series, vol. 26, no. 10, pp. 323-351.

Ritter, W. E.
1900. Some Ascidians From Puget Sound. Collections of 1896 Annals New York Academy of Science, vol. 12, no. 14, pp. 589-616.
(Mainly a description of species.)

Schaefer, Milner B.
1936. Contribution to the Life History of the Surf Smelt _Hypomesus pretiosus_ in Puget Sound. Washington State Department of Fisheries Biological Report no. 35B, 45 pages.
(Includes information on spawning areas and seasons and frequencies of spawning.)

1938. Preliminary Observations on the Reproduction of the Japanese Common Oyster, _Ostrea gigas_, in Quilcene Bay, Washington. State of Washington Department of Fisheries Biological Report no. 38E, 36 pages.

Scheffer, Victor B.
1928a. Dealing With the Seals and Sea Lions of the Northwest. The Murrelet, vol. 9, no. 3, pp. 57-58.

1928b. Precarious Status of the Seal and Sea-Lion on our Northwest Coast. Journal of Mammology, vol. 9, pp. 10-16.

1952. Outline for Ecological Life History Studies of Marine Mammals. Ecology, vol. 33, no. 2, pp. 287-296.

Scheffer, Victor B. and John W. Slipp
1944. The Harbor Seal in Washington State. American Midland Naturalist, vol. 32, no. 2, pp. 373-416.
(General description of habits, seasonal occurrence and distribution, and history of the Harbor Seal in Washington State.)

1948. The Whales and Dolphins of Washington State with a Key to the Cetaceans of the West Coast of North America. American Midland Naturalist, vol. 39, no. 2, pp. 257-337.
(Description of species, records of occurrence and notes on the habits of the cetaceans that occur in Puget Sound.)

Scheffer, Victor B. and Charles C. Sperry
1931. Food Habits of the Pacific Harbor Seal, _Phoca richardii_. Journal of Mammalogy, vol. 12, no. 3, pp. 214-226.

Schultz, Leonard P.
1930. Miscellaneous Observations on Fishes of Washington. Copeia 1930, no. 4, pp. 137-140.
(Includes notes on fish of the San Juan Islands and Lakes Washington and Union.

Schultz, L. P. and W. M. Chapman
1934. A New Osmerid Fish, _Spirinchus dilatus_, from Puget Sound. Annals of Natural History. Tenth series, vol. 3, no. 73, pp. 67-68.
(General description.)

Schultz, Leonard P. and Allan C. DeLacy
1935-36. Fishes of the American Northwest. Mid-Pacific Magazine, vol. 48, no. 4, vol. 49, no. 1-4.
(A catalogue of the fishes of Washington and Oregon with distributional records.)

Schultz, L. P. and R. T. Smith
1936. Is Inopsetta ischyra (Jordan and Gilbert), from Puget Sound, Washington, a Hybrid Flatfish. Copeia 1936, no. 5, pp. 199-203.
(Morphological considerations.)

Shackleford, Martha W.
1925. A Study of Variation in Plankton in Argyle Lagoon. Thesis, University of Washington, Seattle, Washington, 58 pages.
(San Juan Island area, currents, tides, and chemistry.)

Shannon, E. L. and L. C. Altman
1930. Growth in Codium mucronatum. Publications Puget Sound Biological Station, vol. 7, pp. 391-392.
(Concerns rate and localization of growth in the marine green algae Codium mucronatum.

Shelford, Victor E.
1916. Physiological Differences between Marine Animals from Different Depths. Puget Sound Marine Station Publications, vol. 1, no. 14, pp. 157-174.
(Experiments demonstrate relative resistance to chemical and physical changes. Specimens used were collected from Brown Island, San Juan Archipelago.)

1918. The Relation of Marine Fishes to Acids with Particular Reference to Miles Acid Process of Sewage Treatment. Publications Puget Sound Biological Station, vol. 2, no. 39, pp. 97-111.
(Affects of acidity on fishes. Considers treatment of sewage with acids and by product recovery. Material used in experiments collected near Puget Sound Biological Station.)

1930. Geographic Extent and Succession in Pacific North American Intertidal (Balanus) Communities. Publications Puget Sound Biological Station, vol. 7, pp. 217-223.
(Special reference is made to San Juan area.)

Shelford, Victor E. and E. D. Towler
1925. Animal Communities of the San Juan Channel and Adjacent Areas. Publications Puget Sound Biological Station, vol. 5, pp. 33-73.
(Considers general physical and chemical conditions and the major animal communities.)

Shelford, V. E., A. O. Weese, Lucile A. Rice, D. I. Rassmussen, Archie MacLean, Nettie M. Wismer, and John H. Swanson
1935. Some Marine Biotic Communities of the Pacific Coast of North America. Ecological Monographs, vol. 5, no. 3, pp. 249-404. (Covers mainly San Juan and Northern Puget Sound area. A general survey of the extent and dynamics of bottom and shore communities.)

Sherwood, H. P.
1931. The Oyster Industry in North America: A Record of a Brief Tour of Some of the Centres on the Atlantic and Pacific Coasts, and of a Summer in Canada. Journal du Counseil International Pour L'Exploration de la Mer, vol. 6, no. 3, pp. 361-386. (Brief notes on oyster culture in Oyster Bay, Olympia, Washington.)

Smith, Richard T.
1936. Report on the Puget Sound Otter Trawl Investigations. State of Washington Department of Fisheries Biological Report no. 36B, 61 pages.
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SECTION 12: GENERAL SUMMARY

30 June 1954

GENERAL SUMMARY

GEOGRAPHY

Puget Sound as described in this survey includes the inland waterways extending southward into the state of Washington from the eastern end of the Strait of Juan de Fuca. These channels, sounds, and inlets are long and narrow and occupy a basin roughly 90 miles north and south and 40 miles east and west. Mountain ranges surround three-quarters of the area. The water area at mean higher high water is 767 square nautical miles. The principal entrances to Puget Sound from the open ocean are through Admiralty Inlet, between the Olympic Peninsula and Whidbey Island, and Deception Pass, between Whidbey Island and Fidalgo Island.

Puget Sound is the only protected deep water haven on the Washington coast. Major ports, naval installations, and coastal industries are located on its shores. Entrance to Lake Union and Lake Washington is provided by the Lake Washington Ship Canal via the Ballard Locks.

BATHYMETRY

The shape, depth, and coastal topography of the Puget Sound basin are largely a product of glacial activity. Glacier-borne sedimentary materials deposited in a basin between the Olympic Mountains and the Cascade Mountains during the early part of the Pleistocene Epoch were deeply entrenched by stream and glacial action in the latter part of the Pleistocene. The resulting steep-sided valleys, one of which had not been subsequently filled with sedimentary debris now forms Puget Sound. The mainland and island coastlines are irregular and backed by cliffs. The beaches are narrow and confined to embayments, except for tidal flats on the river deltas.

Submerged shallow shelves are extremely narrow or entirely lacking, and in most areas the sea bottom slopes steeply to depths of 300 to 600 feet. The greatest depth of 930 feet is located just north of Seattle. Puget Sound contains several elongated basins that are partially separated from the Strait of Juan de Fuca and from each other by shallow ridges or sills, such as those located in Admiralty Inlet, Tacoma Narrows, and the entrance to Hood Canal where the depths are approximately 150 to 200 feet.

Bottom Sediments

Material on the sea floor varies from rock outcrops, through boulders and cobbles in areas of strong tidal currents, to sand and mud on the slopes. In some areas firm clay and compact glacial till are exposed on the slopes. The bottoms of the deeper portions of the basins are covered with soft mud. The rivers on the eastern shore have developed extensive deltas where their sediment loads are deposited.

CLIMATE

The climate of the area is typically maritime; the summer is cool and the winter mild. At Seattle the monthly average temperature is 39.8° F. in January and 63.8° F. in July. The mean annual temperature is about 50° F.

The prevailing air movement is from the open ocean except during the winter when storms may draw cold continental air into the area. Winds may exceed 60 knots during winter storms but because of the limited fetches the waves rarely exceed 6 feet in height, even in the larger open areas. During most of the year prevailing winds are from a southerly direction but during July and August the prevailing winds at Seattle are from the north. Wind directions are closely related to the local land topography. Average wind speeds are between 7 and 10 knots. Winds exceeding 30 knots have been recorded in Seattle for all months of the year.

As the warm maritime air masses rise over the Olympic and Cascade Mountains heavy orographic precipitation takes place but as these air masses decend and blow over Puget Sound and its adjacent lowland the air masses become warm and only a moderate precipitation occurs averaging between 25 and 50 inches. Most of the rain falls during autumn and winter with minimum precipitation during July and August. The days with appreciable precipitation average 40 percent for the year indicating that the rains are frequent but rarely heavy. Overcast skies occur some 80 percent of the time during the winter.

Snowfall on the lowlands is relatively rare and although it may snow several days during the winter snow rarely remains on the ground for more than a few days.

RIVER RUNOFF

River runoff follows the precipitation pattern; the lowland rivers carrying their greatest volumes during the autumn and winter months. The Skagit River, that drains a mountainous area, in addition has a secondary maximum in summer when the snow is melting. The average runoff of all rivers in the Puget Sound basin is about 40,000 cubic feet per second ranging between monthly extremes of 14,000 and 367,000 cubic feet per second.

TIDES AND TIDAL CURRENTS

The tides in Puget Sound are of the mixed type showing a large diurnal inequality between the heights of succeeding low tides. The average diurnal range at Seattle is 11.3 feet. The maximum range of spring tides rarely exceeds 16 feet. There is a general increase in range as the tide progresses from the Strait of Juan de Fuca to the heads of the inlets with a delay in time of high water of about one hour. Due to the large area of Puget Sound

and its narrow entrances, tidal currents have exceptionally strong tropic velocities attaining 4.7 knots in Admiralty Inlet, 5.1 knots in Tacoma Narrows, and 7.2 knots in Deception Pass. Elsewhere in Puget Sound the tidal currents are generally less than one knot. In addition to their importance in navigation, the strong tidal currents greatly affect the temperature and salinity distribution of the region through their mixing action and their influence on the water exchange.

WATER TEMPERATURE AND SALINITY

Water temperatures in Puget Sound are relatively uniform throughout the year. Because of the mixing produced by the tidal currents, surface temperatures rarely fall below 44° F. even in winter except in the head waters of Puget Sound where the accumulation of cold river waters and relatively quiet conditions will permit the formation of ice during extreme cold weather. The same mixing processes tend to maintain relatively low temperatures during the summer and except in shallow and isolated areas surface temperatures above 60° F. are rare. Because of sills at moderate depths, and the mixing that occurs over such sills, the water in the deeper basins is always relatively warm with temperatures between 44° and 55° F.

Fresh water in large amounts is emptied into Puget Sound from a number of rivers and streams. The greatest amounts are discharged by the Skagit, Stillaguamish, and Snohomish Rivers all located on the north eastern shore. Despite this, the salinity of the waters is remarkably uniform averaging between 29°/oo and 31°/oo except very near the surface where following heavy runoff and light winds a dilute surface layer may occur. Seasonal variations are small. The relatively high salinities are maintained by active exchange of water between Puget Sound and the Strait of Juan de Fuca. Puget Sound is characterized by a net average outflow of the diluted surface water and a net average inflow of more saline water at depth. The salinity of the water in the deeper basins reaches a maximum in late summer or autumn after the subsurface waters in the Strait of Juan de Fuca have reached their greatest salinity and lowest temperatures of the year which normally occurs in August.

MIXING AND FLUSHING

The mixing and flow across the sills which tends to equalize the temperature and salinity in the region are effective in distributing dissolved oxygen and nutrient salts. The depths of the major basins with the possible exception of Hood Canal in summer are well ventilated at all seasons of the year. Subsidiary basins behind deep sills at the extremities of the various arms may not flush from winter until the following autumn, and more infrequently not until the autumn of a succeeding year. These stagnant waters may become almost entirely devoid of oxygen and considerable concentrations of dissolved nutrients such as soluble phosphates and silicates accumulate.

The bottom water in the shallow extremities of the inlets where both the tidal currents and runoff are small also become impoverished in oxygen and enriched in nutrients from spring to fall as a result of the biological activity.

GEOPHYSICAL ASPECTS

Geophysically, the area can be considered as young, mountainous, and fiord-like. No magnetic disturbances of importance to ships navigation have been reported. A number of peaks of the nearby Cascade Mountains are volcanic and have scattered pumice and ash widely from early eruptions, but no eruptions have occurred during the last century.

MARINE BIOLOGY

The area supports an abundant marine flora but no adequate records of local productivity exist. The phytoplankton are most abundant seasonally in spring and summer and locally in the surface waters at the extremities of the various and contributing arms. Here their growth may alter appreciably the distribution of the nutrient salts and dissolved oxygen as well as reducing the transparency of the sea water.

The marine fauna is abundant and varied. A rather extensive commercial and sports fishery, which utilizes both the resident and migratory species, has existed for many years. Of the latter the salmon are most significant commercially.

Nuisance organisms which have deleterious effects on ships, docks, piling, etc. include the marine borers, particularly the teredo (*Bankia*) and the wood gribble (*Limnoria*), and the fouling organisms, notably the barnacles. Although the period of settlement and degree of attack varies with the specific area in which they occur there is no season of the year in which some of the forms are not active.

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